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THEORETICAL CONSIDERATIONS OF THE GENESIS OF ORE DEPOSITS

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Nothing is more noticeable in the history of mining geology than the change which has taken place in the last half-century in the prevailing opinions as to the origin of ore deposits. We may leave out of account the absurdities of Wernerism and most of the earlier speculations of the Plutonist school. Scientific ideas as to the genesis of ores may be said to date from the publication of Breithaupt's epoch-making little book in 1849.[1] Here in the idea of paragenesis we have the germ of modern speculations on this subject. For long, however, the theory of the aqueous origin of all ore deposits held sway in its various forms, one of the best-known of which was the famous lateral-secretion theory. Even yet something very like this theory is held to furnish the best explanation of the origin of certain types, as for example the lead-zinc ores of the Mississippi Valley and other similar deposits. The brilliant writings of Pošepný also did much to perpetuate the reign of water. Nevertheless, at the present time no one will be found to deny that many and important ore deposits are of direct igneous origin. As a matter of fact igneous and aqueous origin are by no means incompatible. It may at once be admitted that watery solutions may be produced direct from magmas. Of this

[1] Breithaupt, *Die Paragenesis der Mineralien*, Freiberg, 1849.

we have abundant evidence in the steam that accompanies volcanic eruptions, and the geysers and hot springs belonging to the later stages of igneous activity in many parts of the world, such as the Yellowstone Park, Iceland, and New Zealand. At Steamboat Springs, Nevada, ores are now visibly being formed by hot springs which must derive their heat from intratelluric sources. It is natural to suppose, therefore, that many of the ancient ore deposits have been formed in a similar way. The common association of ores with propylitization and certain other types of rock-alteration points in the same direction.

Moreover, ore minerals occur in rocks undoubtedly igneous as well as in lodes and veins. Cassiterite is found as an original mineral in granites, in pegmatites, and in quartz veins in undoubted and visible connection with granites. The same applies to its constant companions wolframite and molybdenite. Gold is known in almost every conceivable geological situation of almost every age. Chromium and platinum are found beyond doubt as original constituents of ultrabasic rocks such as peridotites and serpentines. Magnetite and ilmenite have segregated in enormous masses from plutonic intrusions, and so on indefinitely. A great part of the rich mineralization of Mexico and South America is in obvious and visible connection with the great volcanic outbursts ranging from late Cretaceous to modern times. It is clear that a vast number of the most valuable ore deposits are of direct igneous origin. In many other instances, though the connection is not so clear, it is still highly probable or indeed certain.

Nevertheless, although the main fact in its broadest outlines is established, considerable doubt still remains as to the mechanism of the processes by which the concentration and deposition of the ores has been effected, and the underlying and fundamental reasons for these processes. Another highly important aspect of the subject is the distribution in space and time of the different types of mineralization and their relation to crust disturbances and various petrographic types. This in the broadest view is the scope of the study of metallogenesis.

Hitherto it has not been found possible to devise a really satisfactory and logical classification of ore deposits on a genetic

basis. This impossibility is inherent in the nature of the subject, since in nature there exist no sharply defined categories, no pigeonholes into one of which every type will fit. It is the intermediate and transitional types that are the bugbear of any such attempt. Nevertheless there are some basic facts that may be used as a groundwork for generalization. In the first place we have certain ores occurring as original minerals in igneous rocks, and as disseminations and magmatic segregations whose origin from magmas is beyond doubt. Also there are the innumerable instances of ore-bearing pegmatites which can also be assigned with safety to the same origin. A great number of contact and replacement deposits also undoubtedly owe their metal content to transfer from intrusive masses.

It is, however, when we come to the large and highly important class of deposits described in general terms as veins and lodes that difficulties begin to manifest themselves. These undoubtedly grade on the one hand into the magmatic deposits, while on the other hand some of them show distinct evidence of having been formed near the earth's surface at the ordinary temperature and pressure. In dealing with the doubtful members of this group we have to take into account not only the characters of the deposits themselves, but all the attendant circumstances which may throw any light on their origin, such as geographical distribution, relation to sedimentary and other formations of known age, and to the structure, disposition, and character of the surrounding rocks; in short, their geological features. It is the geology of the ore deposits that will throw most light on their origin.

As an example let us take the mining region of western Cornwall, one of the most highly mineralized districts of the world, especially as regards the number of metals found. Here cassiterite occurs as an original mineral in the granite, in pegmatites, in greisens and other pneumatolytic modifications of the granite, in quartz-porphyry dikes, and, most important of all, in a vast number of lodes and veins which chiefly congregate near the contact of granite and slate, almost invariably passing from one rock to the other without interruption. The lodes also show every possible degree of pneumatolytic alteration. Besides cassiterite they

contain wolframite, most abundantly in a comparatively narrow zone near the granite-slate contact. Arsenopyrite is also abundant, and in the upper parts of the lodes, farther away from the granite, tin gradually gives place to copper. Other metals, such as molybdenum, silver, antimony, bismuth, and uranium, are also found, while lead and zinc are abundant in a later series of lodes, usually more distant from the contact. Among the gangue minerals tourmaline, topaz, and fluorspar are abundant. Here the connection of the tin-copper mineralization with the granites and their pneumatolytic phase is obvious. The age of this is also definitely fixed, since the granites cut Upper Carboniferous rocks and the Permian strata are not metamorphosed. The whole of this igneous cycle is a direct consequence of the Armorican crust disturbances which had such an important influence in molding the geological structure of west-central Europe. Very similar phenomena are to be seen in Brittany, in Spain and Portugal, and in the Erzgebirge on both sides of the frontier between the German Republic and Czecho-Slovakia: all of these are broadly contemporaneous with the similar occurrences in Cornwall.

Here we have a clear example of a metallogenetic province, showing a definite association of mineral deposits of a peculiar type with a phase of igneous intrusion dependent on a particular set of earth movements. The number of metals present is very large, but the most characteristic are tin and tungsten, and a special feature observed in Cornwall, Bohemia, and Portugal is the presence of uranium.

Turning now to another region of the Old World, we find a great development of tin ores in the Malay peninsula, in Banka and Billiton, and on the eastern side of the Australian continent from Queensland to Tasmania. In Lower Burma (Tavoy) we find a little tin and much tungsten, so that this evidently forms a slightly varying extension of the same field, a local facies. This tin-bearing region stretches parallel to the great Malayan arc and its continuation into Australia and the mineralization is closely connected with the intrusion of granites, probably of Permo-Carboniferous age. Furthermore, this great province is divided up into subprovinces characterized by special mineral

associations, namely, in Tavoy, dominance of tungsten; in the Malay peninsula, Banka, and Billiton, dominance of tin alone; in Queensland, tin, tungsten, molybdenum, bismuth; in New South Wales, tin, tungsten, and molybdenum; in Tasmania, mainly tin.

The second most important tin-producing country of the world is Bolivia. Here along the Cordilleran chains, in association with the great Tertiary volcanic activity, we find extraordinarily rich veins carrying tin, tungsten, bismuth, and silver; a remarkable and apparently unique type.[1] These veins present features of great interest from the theoretical point of view. Three chief types of veins can be recognized, as follows:

a) Tin-bismuth veins with tourmaline and other pneumatolytic minerals, associated with deep-seated granites.

b) Tin-bismuth-silver veins, carrying most of the tin as complex sulphides, stannite, etc., associated with hypabyssal porphyry intrusions.

c) Silver veins without tin, associated with extrusive volcanic rocks.

A noteworthy feature is the occurrence of the tin in type (*b*) mainly as complex sulphides associated with argentiferous tetrahedrite and sulphosalts of copper, lead, bismuth, arsenic, and antimony. There is thus a distinct gradation in the metal contents of the veins, minerals with boron and fluorine occurring in quantity only in the high-temperature veins associated with granites. Thus the temperature-depth relations of tin and silver are clearly shown.

In all these cases there can be no possible doubt of the association of the tin and other metals with igneous rocks. When we turn to other metals the facts are equally striking. It is impossible to enumerate all of them, but a few examples must suffice, and these may be taken as typical of the rest. It has long been known that platinum has its original home for the most part in peridotites and their alteration product, serpentine, and to a less extent in certain nickel-bearing and other eruptives to be mentioned presently; in short, in ultrabasic and basic rocks. The peridotites also commonly contain large quantities of chromite and also chrome-bearing spinels: hence the presence of chromite is a useful

[1] Davy, *Econ. Geol.*, Vol. XV (1920), pp. 463–96.

indicator of the possible presence of the platinum metals. In the basic rocks also we find large masses of iron ore commonly rich in titanium, either as ilmenite or as titaniferous magnetite. The presence of titanium is specially characteristic of the basic group. Another type of great scientific interest and commercial importance is seen in the great segregations of nickeliferous sulphides found in connection with norites and gabbros, as at Sudbury, Ontario, and Insizwa in Griqualand East. Whatever may be the actual mechanism of the Sudbury nickel deposit, its close connection with the norite intrusion will hardly be denied, and at Insizwa the concentration of the sulphide by some form of differentiation seems clear. In association also with basic rocks, especially with gabbros, are found great masses of pyrite, as at Rörös in Norway, and the cupriferous sulphides of the Huelva district (Rio Tinto and others) also belong here.

In all these cases of the occurrence of ores in basic magmas one point is worthy of special attention, namely, that the ores occur either as disseminations in the rock itself (platinum and chromium in part) or as segregations separated from the magma either by gravity, by diffusion to the margin, or by separation of immiscible liquids. The ore bodies therefore lie either within the intrusion as disseminations, schlieren, or irregular patches, or as a definite layer at its base, or as separate intrusions, often laccolithic in form. Here there is no separation of the ores in pegmatites and all the innumerable varieties of mineral veins, as with the acid rocks, while pneumatolytic effects are subordinate, or more commonly entirely absent. In conformity with this, metamorphic and metasomatic effects are also much less marked. The most characteristic type of basic pneumatolysis is scapolitization, which appears to correspond to tourmalinization in acid rocks, while the concentration of apatite in some instances may also be referred here.

Here another generalization of fundamental importance may be made: the ore segregations of the basic rocks are usually the *first* fraction of the magma to crystallize, those of the acid rocks are usually the *last* fraction. In neither case is the statement invariably true, but exceptions are as a rule due to special causes.

For example, the great iron-ore masses of Kiirunavaara and Luossavaara, as described by Daly, have been formed by the sinking of early-crystallized magnetite in a quartz-porphyry magma. The case of iron ore is, however, exceptional in that it is not specially characteristic of any particular magma, but is of more or less universal distribution.

Although this generalization must not be pushed too far, it is certainly true in its broad outlines. The reason for it is to be found in the presence in, or absence from, the crystallizing and differentiating magma of substances capable of combining with the metals to form volatile compounds, such as fluorine, boron, and especially water. We have every reason to believe that basic magmas do not contain much water; at any rate it is possible to produce basic rocks artificially from dry melts, whereas with acid rocks this cannot be done: some flux is required to insure the crystallization of quartz or orthoclase or hornblende. Such fluxes collect always in the acid fractions of a differentiate, there lowering freezing-points and in particular facilitating the concentration of metals in the last residue of the magmatic solution, which must always tend toward, if it does not actually reach, the composition of the multiple eutectic of the complex solution. In some simple cases the eutectic of quartz and felspar is actually reached, as seen from the simultaneous crystallization of quartz and felspar in graphic pegmatites.

The case of iron is a rather exceptional one, since it is found in considerable amount in connection with igneous rocks of both acid and basic types. The iron-ore masses of Sweden have already been mentioned: here the iron occurs as magnetite, occasionally as hematite, at all events as iron oxides only, and this is the common type in acid rocks. In the basic segregations, however, the state of affairs is generally different: in a great many ultrabasic rocks we find ferrous oxide combined with chromium as chromite, or with magnesium and aluminium in addition as picotite or some allied chromiferous spinel. In the felspathic basic rocks, on the other hand, the greater part of the iron is in some state of combination with titanium, either as ilmenite or as a titaniferous magnetite, whatever that may really be. Again, in the basic rocks iron is

found frequently as sulphide segregations, either with or without copper, nickel, and cobalt. Thus it is seen that although iron as an element is common to both ends of the series, nevertheless it occurs typically in a different state of combination in each.

Having thus arrived at the fundamental generalization that there are two principal groups of ore segregations of very early and very late consolidation respectively, we must now proceed to consider in more detail what particular type of differentiation may be applied in explanation of each.

At the present time five different sets of causes are commonly put forward in explanation of the varied set of phenomena comprised under the head of differentiation, including in this term not only the production of heterogeneity in single intrusions, but also the separation of minor magmas of varying composition from one original magmatic solution. These may be summarized as follows:

a) Marginal concentration of minerals of high freezing-point by diffusion of liquid molecules immediately preceding and during crystallization.

b) Differentiation by gravitational sinking or rising of crystals in a solidifying magma.

c) Separation of a magma into two or more immiscible or partially miscible layers.

d) Assimilation by stoping with its attendant fluxing effects.

e) Squeezing out of liquid residue from a crystalline sponge or network.

This is not the place to discuss the evidence as to the competence of each of these processes as a general factor in differentiation. It is probable that all are applicable in different cases and under different sets of conditions: we have only to consider which of them can be invoked to explain the various types of ore occurrence here already briefly alluded to. It is evident that in the two great groups of ores of early and late consolidation very different physical conditions must prevail, especially as regards temperature and presence of the so-called mineralizing agents or fluxes. In the early group the temperatures must be very high, and we have reason to believe that in the basic rocks fluxes are unimportant; hence it appears that any one of the first three categories should be specially applicable.

Of the first type we have an excellent example in the marginal phase of the gabbro of Carrock Fell, as described by Harker. Here a well-marked segregation of titaniferous iron ore is found along both steeply inclined margins of a laccolith of considerable size, believed to be still more or less in the same position as when intruded. From the figures and description given by Harker it is clear that gravity is excluded, and the only possible explanation is some kind of diffusion to the cooling surfaces during crystallization. The concentration is not very strongly marked, as the most concentrated type of ilmenite-gabbro has only about 25 per cent of iron ore, but at any rate the principle is clear. A very peculiar type is the great mass of titaniferous iron ore at Taberg in Sweden, which forms the central portion of a boss of ultrabasic rock, usually described as hyperite, that is, olivine-norite in modern terms. The reason for this reversal of the normal sequence is unknown.

It will doubtless be generally conceded that it must be difficult on field evidence alone to distinguish between cases of heterogeneity due to gravity-sinking and to immiscibility in the liquid state. In both cases, on complete solidification the heavier rock will be found below, and owing to the high viscosity of fused silicates no very sharp line of demarcation is likely to be seen. It is moreover highly probable that in some instances both causes have been operative. Bowen has brought forward much evidence in support of differentiation by gravity-sinking, and Vogt long ago showed that fused silicates and sulphides possess very strictly limited miscibility.[1] In the well-known instances of Sudbury and Insizwa we have thick intrusions ranging from acid or intermediate at the top to basic or ultrabasic below, with a well-marked layer of sulphides at the bottom. Here it may be suggested that the gradation in the silicate rock is due to gravity with an immiscible separation of sulphide at the base. It seems pretty clear from Daly's latest observations that the concentration of magnetite and apatite at Kiruna is due to gravity-settling of rather large units of differentiation, since many blocks of ore have been caught and fixed at higher levels by increasing viscosity. The occurrence of limited miscibility in silicate solutions is a much disputed point,

[1] Vogt, *Die Silikatschmelzlösungen*, Part I (Kristiania, 1903), p. 96; "Die Sulfid-Silikatschmelzlösungen," *Norsk geologisk tidsskrift*, 1917.

as to which we have as yet no absolute evidence, but it seems quite clear that this cause may be legitimately invoked to explain cases of magmatic sulphide segregations. Vogt has shown by quantitative determinations that the mutual solubility of norite magmas and sulphides is very small indeed; at 1300° C. and one atmosphere, less than 0.5 per cent in the case of pyrrhotite, while copper and nickel sulphides are practically insoluble in norite melts. Moreover, it is improbable that these relations are seriously altered by high pressures.[1]

Up till the present time we have no definite information as to the part played by assimilation and stoping in the formation of ore deposits. In the nature of things such a process would necessarily be difficult to detect, since it would itself destroy its own traces. It is possible, however, that some masses of ore in acid and intermediate rocks may have been introduced in this way, such as the deposits of iron, copper, and gold in magmas of the monzonitic and dioritic facies. This, however, is pure speculation with no tangible evidence to support it. It seems possible that in the earliest solid crust of the earth, afterward remelted, there may have been segregations of metallic ores, afterward reabsorbed and differentiated, as suggested by Morrow Campbell.[2] As to this, likewise, there can in the nature of things be no positive information. It is known that in some localities, for example, southwestern Norway, there is a notable concentration of minerals of the rare earths into syenitic pegmatites, as described by Brögger.[3] If we accept Daly's theory of the origin of alkaline rock types by the fluxing effects of assimilated limestone in normal magmas, it would seem to follow that the concentration of the rare earths here must also have resulted directly from the assimilation. On this question as a whole further information is needed, as few observations are available on the occurrence of ores in connection with highly alkaline magmas.

With regard to the squeezing out of liquid residues from partially consolidated rocks, like water from a sponge, as so graphically

[1] Vogt, *Norsk geol.tidsskr.*, 1917, p. 77.

[2] *Bull. Inst. Min. Met.*, October, 1920, p. 3.

[3] Brögger, *Zeitschr. für Kryst.*, Vol. XVI (1890).

pictured by Harker,[1] this cause may undoubtedly be invoked to explain the separation of pegmatitic material from cooling granites under earth pressure. This process has given rise to areas of pegmatitic permeation, as described by Barrow,[2] in the south-eastern Highlands of Scotland. It is hardly necessary to point out again that pegmatitic mother-liquors often carry notable amounts of ore minerals, and in many instances this seems the most reasonable explanation of ore-bearing pegmatites.

From the foregoing brief and imperfect summary it appears that ore deposits may arise from all or any of the physicochemical processes that have been invoked to explain the origin of heterogeneity in igneous rocks. In some cases one is applicable, in some cases another, but none are apparently excluded on a priori grounds. This variety of origins is only what we should expect from the great differences observable in the characters of the deposits themselves. Here again a correlation can be traced between the nature of the effective process and the physical properties of the molten magmas of different composition and especially the degree of viscosity. Generally speaking, it is admitted that basic magmas are more liquid than normal acid magmas in spite of the higher proportion of water in the latter. Hence differentiation by diffusion, gravity, and immiscible separation are more marked in the basic class, owing to lower viscosity. It is only in the differentiated and concentrated last residues of the acid class that the solution becomes readily mobile and lends itself to formation of veins and pegmatitic permeation. A similar effect is produced by assimilated fluxes in certain cases. These considerations lead again to the same conclusion as before, namely, that the ore deposits of the basic rocks are marginal and basal, or included segregations of a streaky nature if convection currents have been active, while from the acid fluxed magmas are formed veins and lodes in all their varieties, either in fissures in the rock itself, often congregated near its roof, especially in subsidiary domes and cupolas,[3] or actually external to the intrusion, filling fault planes and other fissures and zones of weakness in the

[1] Harker, *Natural History of Igneous Rocks* (1909), p. 323.

[2] Barrow, *Quart. Jour. Geol. Soc.*, Vol. XLIX (1893), p. 330.

[3] Butler, *Econ. Geol.*, Vol. X (1915), pp. 101–22.

country rock. The endless varieties of contact deposits are not here taken into account in detail, but it may perhaps be said that they are more characteristic of acid intrusions, doubtless owing to the abundance of mineralizers, which act as carriers for the metals.

Having thus considered in general terms the phenomena of differentiation and concentration in igneous rocks in their bearing on the origin of ore deposits, it remains to see whether it is possible to draw up a schematic classification on this basis. If this can be done it would constitute a genetic classification of ore deposits in the strictest sense of the word; such a classification, if presented in a graphic form, may be regarded as a genealogical tree of the ore deposits, or rather of the metals, as for this purpose it is hardly necessary to take into account their state of combination; furthermore it is obvious that the characters and distribution of the great class of secondary deposits have no bearing on the point: it is with primary ores alone that we are concerned. Now most primary ores are either native metals, oxides, or sulphides—in some instances arsenic also seems to play the part of an electronegative element, as in enargite and several nickel and cobalt minerals and in arsenopyrite. Furthermore, most primary ores are of very simple composition: the more complex minerals are mostly found in the oxidized ores and in those of the zone of secondary enrichment, with which we are not here concerned.

The primary facts that we have to start on are somewhat as follows:

1. It has been shown that certain metals and non-metallic elements are found chiefly in the basic rocks, including especially nickel, cobalt, chromium, platinum, titanium, with chlorine, phosphorus, vanadium, and sulphur. Iron sulphides, often nickeliferous, are common.

2. Of these, chromium and platinum are specially characteristic of the ultrabasic rocks, themselves usually differentiates of basic magmas.

3. In connection with the extreme differentiation phases of acid magmas are found especially tin, tungsten, molybdenum, zirconium, uranium, lithium, with fluorine, boron, and abundance of water.

4. The rare earths of the thorium-cerium group are found chiefly in pegmatitic phases of granitic and syenitic magmas.

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5. Iron, gold, silver, and copper are of more general distribution, without much tendency to characterize any special type of magma. Iron, however, shows a difference of combination: in the basic rocks it is largely combined with sulphur, titanium, or chromium, in the acid rocks it concentrates mainly as magnetite. Primarily copper is generally combined with sulphur, less commonly with arsenic, wherever it is found.

6. It appears that in the earliest stages of earth history known to us there were two primary magmas, granitic and basaltic: from these the other existing rock types were derived by differentiation.

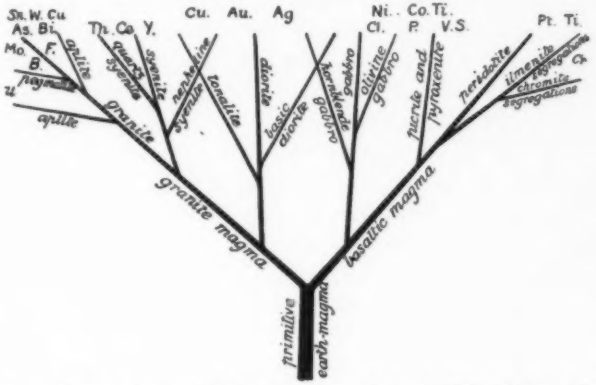

FIG. 1.—Genealogical tree illustrating conceptions of differentiation of igneous rocks and ore deposits from primitive magma.

It is a fair inference that earlier still there was one primitive earth magma of intermediate composition, perhaps a siliceous immiscible fraction, separated from a mainly metallic fraction that formed the heavy core of the earth. In this primitive silicate magma all the valuable metals were at first in solution, afterward separating into its various differentiated fractions according to their partition coefficients, or their degrees of solubility—no doubt assisted by gravity-sinking and fractional crystallization. Some metals seem to have been more or less soluble in all magmas, while others had very decided preferences for a particular type.

It is on the basis of these principles that the genealogical tree here presented (Fig. 1) has been constructed. In its essential

features it is similar to a diagram already published by the writer.[1] The present form of it is, however, slightly more elaborate and the various branches have been arranged in accordance with the silica percentage of the rocks, although the figure must not be regarded as drawn strictly to scale. It is also to be remarked that the thickness and length of the branches do not bear any relation to the actual abundance of the different rock types: in this respect the figure is purely diagrammatic and not quantitative. The angles of inclination between the various branches are controlled only by convenience of drawing. The intercrossing of various branches is, however, intentional, in order to show that similar final products may be obtained from different partial magmas. That is to say that similar rocks and ore types may have different chains of descent from a common ancestor. This is analogous to the biological phenomenon known as heterogeneous homoeomorphy.

This diagram, when looked at from this point of view, is in fact a basis for a truly genetic classification of certain large groups of primary ores; nevertheless it must be regarded as strictly limited in its scope. It takes no account of the secondary ores, or of certain groups which may be of supergene origin, formed by the action of descending meteoric waters. With these classes we are not now concerned. But it is claimed that this systematic arrangement does throw some light on the origin and genetic relationship of the great classes of primary ores, which are of fundamental importance, as being in all probability the original source of all the workable metallic deposits of the globe.

In this treatment of the subject it is necessary to take into account also the conceptions of metallogenetic epochs and metallogenetic provinces, which have been so ably worked out of late years by many writers, especially in America. If the whole scheme of differentiation as here outlined is regarded as continuous, a false impression will be obtained. On the contrary, the processes are discontinuous both in time and space. An admirable summary of the present state of our knowledge of the chronology of ore

[1] Rastall, "Differentiation and Ore-Deposits," *Geological Magazine*, Vol. LVII (1920), p. 298.

deposits will be found in the last chapter of the new edition of Lindgren's *Mineral Deposits*. From this it is clear that the type of mineralization here considered is mainly restricted in time to three periods, pre-Cambrian, Permo-Carboniferous, and Tertiary, corresponding to the greater periods of crustal disturbance and mountain-building. Of these the first is certainly complex and of great length, probably including several periods comparable in magnitude to the two later ones, but as yet it is hardly possible to disentangle these clearly in most parts of the world. The Canadian shield is an exception.[1] Here several distinct periods are distinguishable. Nevertheless it must be remembered that although the now visible manifestations, including the actual deposition of the ores, were spasmodic, the genetic processes are undoubtedly in constant operation in depth, elaborating the material and preparing the way for the igneous outbreaks and accompanying ore-formation that occur whenever the static equilibrium of the crust is disturbed, whatever may be the cause to which these disturbances are due. This is a fundamental question into which we cannot now enter.

[1] See Miller and Knight, *Trans. Roy. Soc. Canada*, Vol. IX (1915), pp. 241–49.

NOTE ON A POSSIBLE FACTOR IN CHANGES OF GEOLOGICAL CLIMATE

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In a recent discussion of the factors that control variations of world climatic conditions, Professor Humphreys has criticized the various astronomical hypotheses that attempt to explain the ice ages and other features in geological climate.[1] Several factors, formerly given weight, are held responsible only for effects of the second order at most. Among the insufficient interpretations he would place Croll's theories which involve the changing elements of the earth's orbit, and the various hypotheses connecting sun spots (and other intrinsic changes in solar radiation) with terrestrial insolation and the climates of the geologic past.

The primary factors of climatic control clearly appear to be of terrestrial origin—land elevation (and its concomitant factors of oceanic and atmospheric distribution and circulation), combined with vulcanism. Cosmic factors are evidently not of primary importance. The observed connection of climatic phenomena with land elevation can by no means be attributed to chance. A cosmic non-terrestrial origin for the principal factors of climatic control would therefore leave unexplained such significant coincidences as mountain forming and glaciation, since one could hardly propose seriously that cosmic factors are the cause of both topographic and climatic change.

One astronomical possibility that I believe has not been urged heretofore appears, however, as a result of recent observation, to deserve attention as a potential secondary factor in recorded geological climates, and possibly even as a primary agent at some prehistoric time.

[1] W. J. Humphreys, "Factors of Climatic Control," *Jour. Frank. Inst.* *CLXXXVIII* (1919), 775; *CLXXXVIII* (1920), 63.

1. Barnard, Wolf, and others have shown the very common existence of extensive, diffuse, irregular, luminous and non-luminous nebulosities in the sky, and I have previously called attention to the apparent affiliation of Barnard's dark nebulae with our local cloud of stars; Hubble's unpublished observations appear to substantiate this affiliation of the dark markings and demonstrate their relative proximity to the solar system.

2. The great Orion nebula is one of the luminous or partially luminous members of this group of nebulosities, and spectroscopic observations by Fabry, Frost, and Campbell and their associates have shown that its various parts are moving relative to each other with velocities of several kilometers a second.

3. In and near the Orion nebula more than seventy faint stars that vary in light have been found at the Harvard, Heidelberg, and Yerkes observatories, and elsewhere; Lampland has also found similar variables in the comparable nebula Messier 8. My work on the variables in Orion has shown: (*a*) no certain periodicity in the variation, (*b*) light curves not comparable with known types, (*c*) a variety of color types among the variables, and (*d*) no evidence of great range or of extinction (as would be expected from occultations).

4. Van Maanen's discussion of the proper motions supports the inference, based on the distribution of the variables, that they are really associated with the Orion nebula and with the cluster of brighter stars in that vicinity. The distance of this group of stars, according to Russell and Kapteyn, is six hundred light-years. The diameter of the region throughout which these peculiar variables are known is fifty thousand times the diameter of Neptune's orbit, and the total nebulous region in Orion is many times larger. (From the present direction and amount of their motions, we compute that a few million years ago our sun was in the vicinity of the Orion nebula; at its present speed the sun would require nearly a million years to pass through that particular nebulous region).

5. From the known distance of the variables in Orion, and my measures of their apparent magnitudes, it is easily computed that in luminosity they are dwarfs. This supports the conclusion from the study of their light curves that the Orion variables differ

from all other types of variables, which almost without exception are giants in luminosity.

6. In view of (*a*) the irregularities of the light variations, (*b*) the apparent immersion of the variables in nebulosity, and (*c*) the spectroscopic evidence for the irregular churning about of this nebulous matter, it seems reasonable to believe that the variations in brightness result from collision or friction with the irregular nebulosity in which the variables are involved. The encounter of star with nebula is at present the best, though perhaps not an entirely satisfactory, explanation of the cause of galactic novae; and it is the only hypothesis that has been suggested to account for temporary stars in the rapidly moving spiral nebulae.

7. Long-exposure spectrograms of the Orion nebula, using the 100-inch reflector and a rapid focal-plane spectrograph, have recently shown in the bright-line spectrum the presence of hydrogen, nebulium, helium, carbon, and nitrogen; they also show a faint continuous spectrum in all parts of the nebula.

8. The bearing of the foregoing observations on the question of geological climates becomes obvious when we note the following points: (*a*) The condition that causes variation of a star in the Orion nebula must also gravely affect the atmosphere surrounding any attendant planet. (*b*) The sun is moving with a velocity of 20 kilometers a second through a region of space, large sections of which are known to be occupied by diffuse nebulosity (most of it probably much less dense than that in Orion). (*c*) The observed variation of the friction variables in Orion is generally from 20 to 80 per cent of the total light, and sometimes appears rapidly oscillatory, sometimes secularly progressive, sometimes a discontinuous brightening or dimming. (*d*) A change of 20 per cent in the solar radiation, if maintained for a considerable period of years, would sufficiently alter terrestrial temperature to bring on or remove an ice sheet; an 80 per cent change, unless counteracted by concurrent changes in the terrestrial atmosphere, would completely desiccate or congeal the surface of the earth.

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THE PLEISTOCENE SUCCESSION NEAR ALTON, ILLINOIS, AND THE AGE OF THE MAMMALIAN FOSSIL FAUNA

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Some time previous to 1883 the late Honorable William McAdams, an ardent naturalist of Alton, Illinois, collected a number of mammalian remains from the Quaternary deposits of the Mississippi bluffs near his home city. The specimens found their way to the United States National Museum at Washington, where they have been studied by Dr. O. P. Hay. The collection includes remains of a ground sloth, horse, peccary, a large deer, moose, reindeer, eland, musk ox, mastodon, beaver, ground hog, pouched gopher, and brown bear.[1] Their importance became obvious when some of the individuals were found to represent new species, and therefore it was especially desirable to ascertain if possible their stratigraphic horizon.

The attention of the writer having been called to this collection through the kindness of Doctor Hay, arrangements were made with the Illinois Geological Survey for a few days' study with the hope of finding the exact locality and horizon, and of determining the place of the deposits in the Quaternary series. The deposits proved to be so suggestive of new interpretations that this preliminary paper has been prepared.

Previous literature.—In 1882 A. H. Worthen noted the finding of a portion of the jawbone of a mastodon in the lower part of the loess just northwest of the city of Alton.[2] In 1883 McAdams published an abstract of a paper in the *Proceedings of the American*

[1] O. P. Hay, personal communication.

[2] A. H. Worthen, "Geology of Madison County," *Economical Geology of Illinois*, Vol. I (1882), p. 252.

Association for the Advancement of Science which he read at the Minneapolis meeting. Quoting from this paper[1] we read:

> The drift clays proper at Alton, Illinois, had a maximum thickness of about one hundred feet, and the bluff clays were nearly of the same thickness. These clays were remarkably rich in animal remains, such as teeth and bones, attached to calcareous nodules or claystones. Remains of thirteen different species, now perhaps all extinct, had been found. The rodents were well represented by bones of seven species, including three or more beavers and some gophers. Nearly seventy teeth were found in the Quaternary deposits, a majority of them in a single quarry.

The locality.—The bluffs northwest of Alton have a height of from 125 to 175 feet above the Mississippi River. Approximately 75 to 125 feet of the section is Mississippian limestone, while the overlying material consists largely of loess with a thin deposit of glacial till in places separating the loess from the limestone. The upper surface of the limestone is somewhat uneven, but the cliffs persist for many miles up the river. Just east of Alton the Mississippian formations give way to the Pennsylvanian sediments. The upland of the western part of the city is characterized by karst topography, due to the solvent action of ground water on the underlying Mississippian limestone.

Section at one of the quarries.—At Plant No. 2 of the Mississippi Lime and Material Company, northwest of the roundhouse, the following section was found:

	Feet
Soil, loessial, dark brown, leached	1
Loess, brownish at the top, grading below within a few feet into buff; leached 4 to 5 feet below the soil; calcareous below, with a few loess fossils scattered through the deposit; stands with steep face in fresh cuts; maximum thickness . . . . . about	20
Loess distinctly more reddish than the overlying, strongly suggesting a distinct deposit; contains many fossil snails, some "pipestem" concretions; has a silty texture but not sandy; maximum thickness . . about	30
Glacial till, reddish, contains many erratic pebbles of granite, dolerite, greenstone, quartzite, and other Canadian rocks, and also some local rocks, mostly subangular, some	

[1] *Proc. A.A.A.S.*, Vol. XXXII (1883), pp. 268–69.

rounded. The till is much more oxidized than the overlying loess. In the contact zone between the till and the loess are the lime concretions from which the mammalian remains were obtained.[1] Thickness . . .	1–3
Limestone, Mississippian age, about	100

Salient points regarding the drift.—As noted above, the glacial till exposed at this quarry is very thin and much more oxidized than the overlying loess. At the next quarry to the northwest, a patch of glacial till about 12 feet thick lies beneath the loess, strikingly set off from the loess above by a chocolate brown, weathered zone. The face of the exposure above the limestone cliff was too precipitous to admit of detailed study, but in the succeeding quarry to the northwest, at Plant No. 3 of the Mississippi Lime and Material Company, near the northeast end of the quarry, 18 feet of till above the limestone and below fossiliferous loess was accessible for study.

The till is a typical pebbly clay till. Its top is rounded and marked by a pebble band. The till is also oxidized to dark brown, changing below within a few feet to a yellowish brown to yellow color. The matrix of the till and the limestone pebbles are leached for about 8 feet down from the summit of the till, but where the slope of the till cuts down to a lower level this leached zone is diminished to about 3 feet. Beneath, the till is highly calcareous, and contains lime concretions up to about 8 inches in diameter. No such concretions occur in the overlying loess. The drift breaks into small polyhedral forms, due to the numerous intersecting joints. The surfaces of these joints are coated with oxide of manganese.

Age of the drift.—That the drift is much older than the loess is clearly shown by the weathered zone at its top. Its geographic location brings it within the possibility of being Illinoian in age; but there are strong suggestions that it may be as old as the Kansan. The 8-foot depth of the leached zone beneath fossiliferous and calcareous loess, the chocolate brown color of the upper part of the oxidized zone, the coating of manganese dioxide along the numerous joints which transect the till body, and the large concretions

[1] Fortunately the writer was able to have Mr. John D. McAdams, son of the collector, verify the horizon and the concretions as the source of the fossils.

in the calcareous zone, representing a concentration of part of the lime formerly in the upper portion, are somewhat extreme for drift of Illinoian age, underlying calcareous loess. The significance of these evidences seems even greater when one takes note of the pebble band at the top and the rounded summit which indicate the removal of an unknown amount of the leached drift. That this erosion was considerable and took place before the deposition of the loess is further suggested by the patchy distribution of the drift.

The evidences of great age stimulate a search for the nearest known Kansan drift. Drushell describes several exposures of much weathered drift, believed to be Kansan, in St. Louis.[1] And Fenneman states that the vicinity of St. Louis "apparently contains the thin edge of the Kansan drift sheet," as well as that of the Illinoian drift.[2] The Kansan drift of northern Missouri being in the Keewatin field, the question arises as to whether the remnants of drift at Alton may not record the movement of the Kansan ice across the site of the present Mississippi Valley. An examination of the petrology of the Alton deposits, made with the capable help of Dr. T. T. Quirke, supports an affirmative answer. None of the pebbles, so far as known, is distinctively from ledges in the Labrador field, whereas, all of them may well have come from formations in the Keewatin field, a few strongly suggesting native ledges at the west end of Lake Superior.

Some negative evidence, however, is to be considered. Leverett has observed two occurrences of glacial striae on bedrock at Alton, whose trend is S. 30°–40° W.[3] Although referred to the Illinoian ice, they were probably made by whatever glacier deposited the overlying till. If the drift is Kansan and of Keewatin relationship, the ice lobe in northern Missouri must have radiated until the eastern peripheral part moved in a northeasterly direction (E. 50°–60° N.)—a seemingly extreme departure from the main movement

[1] *Jour. Geol.*, Vol. XVI (1908), pp. 493–98.

[2] "Geology and Mineral Resources of the St. Louis Quadrangle," *U.S. Geol. Survey*, Bulletin 438, p. 31.

[3] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Survey*, Monograph XXXVIII (1899), pp. 86–87.

of the lobe. Hence, from this standpoint, it seems better to credit the striæ to an ice sheet coming from the northeast, and to inquire into this possibility.

Pre-Illinoian drift in the Labrador field has been identified in surface exposures in the western part of the La Salle quadrangle and the eastern part of the Hennepin quadrangle.[1] Drift below the Illinoian has also been reported in a recent well in the Springfield region.[2] Such drift is far enough east of the known limits of the Keewatin field to be best referred to the work of a glacier in the Labrador field having a general southwesterly movement in Illinois. But, as pointed out above, the materials collected from the Alton deposits do not show anything distinctively Labradorean in origin. More data must be awaited to settle definitely the age of the drift concerned.

The loess deposits.—As given in the section described above there are two deposits of loess in this region, separable at least on the basis of color. The lower loess is characterized by its reddish tinge, the upper by its buff color. At all of the fresh exposures of the several quarries at Alton, this difference is conspicuous, and this is found to hold not only for street cuts in other parts of the city but for more distant localities. Buff loess overlying reddish loess is shown at the quarries at Grafton, 18 miles up the river, and at Edgewood, about 25 miles down the river. At Alton the reddish loess is somewhat thicker than the buff, the former being about 30 feet thick, the latter about 22 feet. Approximately the same ratio holds true at Grafton, but at Edgewood the conditions of slope do not favor a good estimate. Both are fossiliferous, but on the whole the lower seems to contain more shells than the upper. The fossil content will be discussed later. In texture, both seem to be typical loess, with no notable quantity of sand or suggestion of stratification.

Both are doubtless aeolian in origin, their relations to the Mississippi Valley indicating its flood plain as the chief source of

[1] Gilbert H. Cady, "Geology and Mineral Resources of the Hennepin and La Salle Quadrangles," *Bulletin 37* (1919), p. 71.

[2] E. W. Shaw, and T. E. Savage, "The Tallula-Springfield Quadrangles," *U.S. Geol. Survey*, Folio No. 188 (1913), p. 7.

supply. The distinctness between the two in color remains to be explained. Three working hypotheses may be tested. (1) The difference in color is original, the lower having been derived from a reddish silt, the upper from a buff silt. (2) The difference in color was brought about by weathering of the lower loess before the upper was deposited. (3) The lower was deposited under climatic conditions which favored oxidation to a reddish tinge during accumulation and then with a change in climate the succeeding deposits were not so highly oxidized, only a buff color being produced. The first and third hypotheses do not necessarily imply a distinct interval between the two stages of deposition, while the second, of course, does. A solution was sought in the nature of the contact, the evidences of weathering, and the fossil content.

1. *Character of the contact.*—In perhaps most places the contact between the two loesses is gradational, the gradation, however, taking place within a few inches. At first glance, this might be taken to record continuous deposition. But such an interpretation must not be held too rigidly in the case of wind deposits, since materials of an old surface may be mixed with new sediments, either by the wind itself or by organic agencies, thereby obscuring the record of an interval.

2. *Difference in oxidation.*—The reddish tinge of the lower loess is somewhat greater at the top than lower down in this deposit, although the reddish tinge characterizes the whole deposit. The stronger color at the top of the lower loess suggests an interval of weathering before the deposition of the overlying, but the reddish tinge throughout must be otherwise explained.

3. *Differences in content of lime carbonate.*—If the lower loess was subjected to weathering, it should show evidence of leaching of lime carbonate. The acid test revealed the presence of some lime carbonate throughout the reddish loess and into the overlying buff loess, but the reaction was notably feebler in the top of the reddish loess than in the base of the buff. While not strong, this evidence is suggestive of at least a brief interval of weathering between the two loess epochs although it is realized that there may have been an original difference in the lime content of the two loesses. Some of the larger shells, such as the *Polygyras* which extend from bottom

to top in the lower loess, are more fragile in the upper part, thus strengthening the evidence of leaching.

4. *Bearing of the fossil content.*—A small collection of fossils from each of the two loesses was made, and these have been examined by Curator Frank C. Baker of the Museum of Natural History, University of Illinois. The fact that the collection was not exhaustive limits the conclusions that may be drawn as to the fossil differences between the two deposits. However, two points seem to be clear: first, the lower loess has notably more fossils than the upper; and secondly, the large *Polygyras*, so characteristic of the lower deposit, do not seem to pass into the upper. Two of these *Polygyras* have been designated new varieties by Professor Baker; one, *Polygyra profunda pleistocenica*, is smaller than the normal species of today, and the other, *Polygyra multilineata altonensis*, is larger than its living representative. These and some of the other forms are described in a paper by Professor Baker.[1] If these should be found to be limited to the lower loess, the fact might indicate some climatic condition of unusual character.

From the foregoing evidence it would seem that a brief epoch intervened between the deposition of the reddish loess and the buff loess, but that the difference in color is not wholly due to this epoch of weathering. There is the possibility that the reddish tinge was given the lower loess by oxidation during the period of accumulation, but this would imply a climate of rather moist and dry extremes. The helices of the lower loess, such as *Polygyra profunda* and *multilineata*, according to Baker, are fond of relatively damp places in forest litter, beneath old logs and rubbish, and hence seem to be negative evidence. However, the *Polygyras* of this deposit have variational differences from these types, and these differences may be significant in this respect, although this is conjecture. The alternative view that the reddish tinge is due to the original color of the silts which were then present on the Mississippi flood plain, is somewhat favored. Reddish silts beneath loess are known upstream at least on the Iowa side where they are described as "red loam."[2] The writer has also observed "slack-

[1] *Nautilus*, Vol. XXXIV (1920), pp. 61–66.

[2] W. H. Norton, "Geology of Scott County," *Iowa Geol. Survey*, Vol. IX (1899), pp. 486–88.

water" silts of various colors, including maroon, in a tributary to the Mississippi River near Clinton, Iowa. Although these silts are believed to be younger than the "red loam," they help to show that the Mississippi has carried reddish silts at different times.

The age of the loesses.—The occurrence of the loess on the weathered till shows that for a long time after the deposition of the glacial till there was no loess in this vicinity. If the drift is Kansan in age, the reddish loess may be Sangamon; if, on the other hand, the drift be Illinoian, the reddish loess probably is Peorian. It is unlike any Peorian loess of which the writer knows, but the color does not necessarily preclude that possibility.

The upper buff loess is leached to a depth of 5–6 feet from the surface—an amount not exceeding some instances of leaching of loess on the Early Wisconsin. However, the summit is somewhat rounded, favoring some slope-wash, and hence this figure probably does not represent the total amount of leaching. According to Curator Baker, one species (*Pyramidula shimekii*), typical of the Early Peorian loess,[1] occurs in the collection taken from the buff loess but not in that from the reddish loess. The thickness is unusual for post-Wisconsin loess, but its proximity to the Mississippi makes this possibility plausible. Thus, the evidence in hand is not decisive as to whether the upper buff loess is Peorian or Early Wisconsin. If the reddish loess is Sangamon in age, the absence of a record of a long interval between its deposition and that of the overlying buff loess would seem to tie the two rather closely and favor the Early Peorian age of the upper loess.

The mammalian fossil horizon.—Mr. McAdams reported the mammalian fossils to be associated with calcareous concretions in the lower part of the loess.[2] They occur, however, at the base of the loess and the top of the till. Scores of concretions were broken open and examined in the hopes of finding more fossil remains, but reward was had in but one specimen, which contained a remnant of the lower portion of some tooth of an unknown mammal. A quarryman at Plant No. 2 reported that in the summer of 1919 a

[1] Formerly called Iowan loess, but recently pointed out as Early Peorian in age: "The Iowan Drift a Review of the Evidences of the Iowan Stage of Glaciation,," *Iowa Geol. Survey*, Vol. XXVI (1917), pp. 140–64.

[2] *Proc. A.A.A.S.*, Vol. XXXII (1883), p. 268.

fragment of a jawbone with teeth was found attached to a concretion when the overlying clay was being washed away by the hydraulic method. Unfortunately, the specimen was not saved.

The concretions range in size commonly from 1 inch or less to 5 and 6 inches in their longest diameter. Some include *Polygyra* shells, characteristic of the lower loess from bottom to top, while others contain pebbles of the underlying drift. A large percentage of each concretion appears to be of very fine material, which has given them the name of "loess nodules," although they do not occur strictly in the loess. They are secondary, younger than both drift and loess, their content of lime having been dissolved from the overlying formations which, together with the finely divided material of the loess carried probably in the colloidal state, has been deposited in concretionary form in the contact zone between the loess and the drift. In the forming of some of these concretions some of the pebbles in this zone were included, and, in some instances, mammalian remains.

Composition of the fauna and its age.—The following is a list of species which have been identified by Dr. Hay[1] in the McAdams collection:

Megalonyx jeffersonii	Extinct ground sloth
Equus sp. indet.	Extinct horse
Platygonus cumberlandensis?	Extinct peccary
Sangamona fugitiva	Large extinct deer
Cervales roosevelti?	Extinct moose
Rangifer muscatinensis?	Extinct reindeer
Taurotragus americanus	Extinct American eland
Symbos promptus	Extinct musk ox
Mamut americanum	Extinct mastodon
Castor canadensis	Canadian beaver
Castoroides ohionensis	Extinct giant beaver
Marmota monax	Ground hog
Geomys bursarius	Pouched gopher
Ursus americanus	Brown bear

The quarry from which most of the remains were secured shows a gentle depression at the top of the limestone, as if the surface of the limestone led to a sink, such as characterizes the karst topography of the upland directly back from the quarries. An examination of two of these sinks revealed their origin to be joint

[1] Personal communication.

planes widened by solution. At the quarry, several solution channels are well exhibited and the faces of the rock along the joints are in some instances coated with travertine, and in others with silt or clay which has been carried down from the surface. The clogging of these subterranean channels would give rise to ponds in the surface sinks, modern examples of which occur a short distance north of Plant No. 3 of the Mississippi Lime and Material Company. Such situations may have existed during the Pleistocene, and if so, offered favorable conditions for the entrapment of the region's fauna of both water and land species.

The fossil fauna, according to Baker, contains certain elements which suggest the arctic phase of a glacial epoch and other elements which belong to the warm phase of an interglacial epoch. The remains, however, could not have lain on the drift during the long period of weathering which followed the deposition of the drift. Hence, it is thought the remains of the arctic elements are a record of the life which lived in the latter part of the next glacial epoch, while the remains of the warm fauna represent the life which lived at the beginning of the interglacial epoch following that glacial epoch. As the melting of the ice sheet was a response to the change of climate from cold to warm, it is believed that with the local disappearance of the ice sheet, the warm interglacial fauna succeeded the arctic before the deposition of the reddish loess.

If the till proves to be Kansan in age, the weathering of the drift may be credited to the Yarmouth interglacial epoch, the mammalian fauna to late Illinoian and early Sangamon times, the reddish loess probably to the Sangamon, and the buff loess to the Iowan. If, however, the till is Illinoian, then the fauna probably is a partial record of the life of the latter part of the Iowan glacial epoch and the early Peorian interglacial epoch. In the latter case, the writer finds some difficulty in assigning both loesses to the Peorian, or in referring the upper buff loess to post-Wisconsin times. However this may be, the Illinoian and Sangamon epochs are post-mid-Pleistocene, from the standpoint of the duration of the Pleistocene, and the fauna represented by the McAdams collection may be regarded as post-mid-Pleistocene.

THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

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III

ON THE QUARTZ, CRYSTALLIZING AT A LATE STAGE, IN QUARTZ-BEARING NORITES, GABBROS, SYENITES, DIORITES, ETC.

In the rocks here mentioned, where the quantity of quartz does not surpass 5 per cent or occasionally—especially in some quartz-diorites[1]—somewhat more, the quartz, as is well known, appears as *Zwischenklemmungsmasse*, or mesostasis, indicating a very late stage of crystallization. If we for convenience' sake only concern ourselves with the gabbroidic rocks, we find this depending on the fact that in a complicated system (Ab+An:ferromagnesian metasilicates [with other pyroxene components]:Qu), a great deal of plagioclase and pyroxene will crystallize at an early stage if the Qu component is present only in small quantity. By this means the quantity of the Qu component in the mother-liquid increases, and the quartz can only commence forming when a complicated eutectic boundary between Qu and Ab+An and ferromagnesian silicates has been reached.

In this manner the quartz will fill the intervening spaces between the already formed plagioclase and pyroxene individuals. At this late stage of crystallization, however, we have not, as occasionally assumed by some earlier investigators, a crystallization of quartz alone, but, on the contrary, of quartz simultaneously with some plagioclase and ferromagnesian silicate. The fact is that the quartz in the mesostasis often forms a pegmatitic or granophyric intergrowth as well with the plagioclase as with the pyroxene in

[1] Rocks with acid plagioclase, with at least 15 per cent quartz, I do not include in the group of diorites.

question. As an example we refer to Figures 17 and 18 of a quartz-norite from Erteli, Norway, consisting of about 60 per cent labradorite, 35 per cent hypersthene (with a little secondary hornblende), and on the average 5 per cent quartz, but without oxidic iron ore and without biotite. Some parts of the thin section show only ½, 1, or 2 per cent of quartz, but locally, as in the part photographed, the quantity of quartz rises much higher, even to 20 per cent.

The relative proportions of the three minerals of the last stage of crystallization cannot be accurately defined under the microscope. We get the impression, however, that the percentage of

FIG. 17.—Photomicrograph between crossed nicols (24:1).

FIG. 18.—Drawing (27:1)

Hyperitic-structured quartz-norite from Erteli, Norway. Labradorite, with twinning lamellae after the albite law (and quite subordinate after the pericline law). Hypersthene (dark shading) with a little secondary hornblende. A little orthoclase (dotted in diagram) at the periphery of one or two labradorite individuals. The drawing represents about seven-eighths of the photomicrograph.

ferromagnesian silicates in the final product of the solidification is quite small. As an estimate we may rate about 55 per cent labradorite, 35 per cent quartz, and 10 per cent pyroxene.

Their mutual proportions, however, will to a great extent be dependent upon the composition of the plagioclase and the pyroxene.

Originating from the values mentioned, we may imagine a norite or gabbro with 3.5 per cent quartz, where the quartz and

the remaining part of the final product will commence to crystallize only after all in all 90 per cent plagioclase and pyroxene have solidified.

As is well known, a little orthoclase or microcline often appears with the quartz in the mesostasis of the gabbro rocks. The explanation of this fact is quite simple. If the magma contains somewhat more Or ($KAlSi_3O_8$) than is absorbed by the plagioclase, the small surplus of Or will be concentrated in the final magma, and consequently will crystallize together with the quartz and some plagioclase and ferromagnesian silicate in the mesostasis.

In the chapter in Part II on the "Oligoclase-Granite Dikes" of many gabbros and norites, we will show that these dikes represent the final magma, resulting at a very late stage of the crystallization of gabbroidic magmas which contain a little quartz.

ON THE DIFFERENCE BETWEEN THE SOLUBILITY OF THE FERROMAGNESIAN SILICATES IN ACID (GRANITIC) AND BASIC (GABBROIDIC) MAGMAS

We shall commence by mentioning some binary eutectics.

Synthetic determinations, according to the Geophysical Labaratory, Washington:

Qu (crystobalite, *ca.* 1650°):An (1550°)=48 per cent Qu:52 per cent An (1353°).

Qu (crystobalite):Diops (1391.5°)=16 per cent Qu:84 Diops (1362°).

An:Diops=42 per cent An:58 per cent Diops (1270°).

Ab (*ca.* 1100°):Diops=about 97 per cent Ab:3 per cent Diops. (The last statement is according to extrapolation by Bowen.)

Analytical (see above) Qu:Ab=about 28 per cent Qu:72 per cent Ab.

For the Na_2O-rich granites containing pyroxene instead of the usual biotite we must assume that Qu:Ab:Diops (at high pressure) form a ternary eutectic. The same must be assumed also for Qu:An:Diops. The latter system, however, is of subordinate interest petrographically. For the ternary systems Qu:Ab:Diops and Qu:An:Diops, with regard to which we know all the binary eutectics between the individual substances, we shall construct the approximate ternary systems, Figure 19. We here especially fix our attention on the fact that the ternary eutectic Qu:Ab:Diops can contain no more than a few per cent, or probably not even so much, of diopside. On the other hand,

the eutectic boundary-line between diopside (or pyroxene in general) and anorthite, bytownite, and labradorite (see above) contains as much as about 55, 45, and 35 per cent pyroxene respectively, and these figures will only be displaced to a slight degree by the presence of a lesser quantity of quartz, as 2, 5, or 10 per cent.

In magmas of *granitic* composition, with Ab as the plagioclase, diopside must consequently commence crystallizing earlier than plagioclase (albite), even if only as little as a few per cent of diopside are present. In magmas of *gabbroidic* composition (with labra-

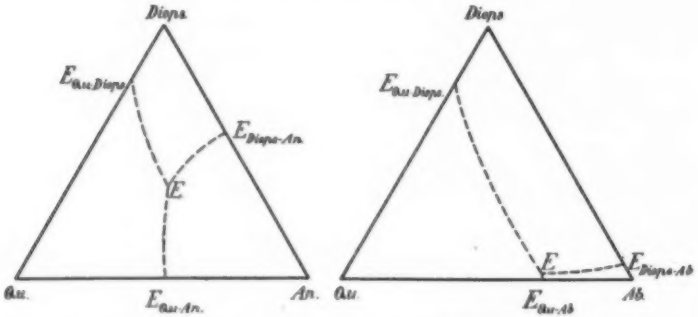

FIG. 19.—Diagrams of the individualization fields Qu:Diops:An, and Qu:Diops:Ab.

dorite or bytownite), on the other hand, plagioclase commences crystallizing earlier than the pyroxene, even if as much as 35–40 per cent of pyroxene is present.

This result with regard to the slight solubility of $CaMgSi_2O_6$ in acid magmas, deduced from physico-chemical foundations, is verified by the petrographical investigation of granitic igneous rocks. And this slight solubility in the acid igneous rocks $\ddot{F}e$ applies not only to diopside, but also to the Mg, Ca-, Mg, $\ddot{F}e$, Ca-, or Mg, $\ddot{F}e$-silicates in general.

It is apparent that—

1. The crystallization of the silicates in the granites (with about 70–76 per cent SiO_2) commences with the crystallization of the ferromagnesian silicates (biotite, hornblende, augite, hypersthene) when the latter is present in a quantity of at least a few

per cent. With more basic plagioclase (andesine) somewhat more of the ferromagnesian silicate must be present if the latter is to commence crystallizing earlier than the plagioclase.

2. In the granitic eutectic we only find a trifle MgO, viz., according to the analyses collocated on page 348, we find in magmas with little An only about 0.2 per cent MgO (and in the magmas, somewhat richer in An, possibly as much as about 0.5 per cent MgO).

The very great difference between the degree of solubility of ferromagnesian silicates (mica, pyroxene, or hornblende) in *acid* rocks, consisting chiefly of acid feldspar and quartz, and in *basic* rocks, containing basic plagioclase, is of great petrologic importance.

ORTHORHOMBIC AND MONOCLINIC PYROXENE

In orthorhombic pyroxene we often observe microscopically small lamellae of monoclinic pyroxene, and in monoclinic pyroxene corresponding minute lamellae of orthorhombic. This must (see above, p. 436) be explained as a secondary phenomenon, due to a secretion in the solid phase.

Where *independent* individuals of orthorhombic and monoclinic pyroxene are intergrown, the orthorhombic (hypersthene)—as has often been pointed out by earlier investigators and as I have often observed in norites containing diallage—forms the kernel and the monoclinic (diallage) the surrounding parts. This indicates that the hypersthene was formed earlier than the diallage. Exceptionally also we find large crystals of hypersthene, with quite good idiomorphic outlines, inclosed in the diallage.

We here refer to Figures 20–21 of a norite,[1] containing diallage, from Skjækerdalen in Norway, and consisting of about 5 per cent olivine (according to the determination of the optical character and the axial angle with 20–25 per cent Fe_2SiO_4) in scattered individuals (not represented in the section drawn); about 25 per cent hypersthene (according to optical determination with about 25 per cent $FeSiO_3$); about 25 per cent diallage (optically positive, $2V = ca.\ 65°$, $c:c = ca.\ 43°$) with a little primary brown hornblende;

[1] This rock has recently been treated by C. W. Carstens, *Geology of the Trondhjem District*, 1920, p. 101.

about 40 per cent labradorite (about Ab_2An_3); and about 5 per cent pyrrhotite. If we leave out of consideration the olivine, which appears only here and there and whose age we were unable to determine with certainty in the present case, the hypersthene is the oldest mineral, as it shows an idiomorphic contour against all the other minerals—however, with somewhat rounded edges. (See the remarks in a following chapter.)

We especially emphasize that crystals of hypersthene in several places have swum together to small aggregates, showing a synneusis structure (see the left side of Fig. 21), and that the hypersthene shows idiomorphic outlines also against the diallage, with

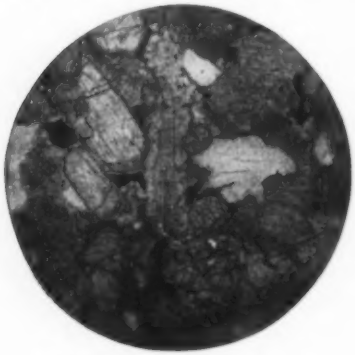

FIG. 20.—Photomicrograph (15:1)

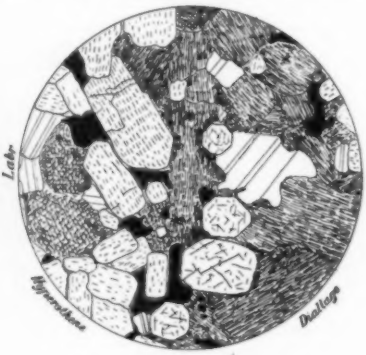

FIG. 21.—Drawing (15:1)

Norite from Skjækerdalen, Norway. Contains hypersthene (in the photograph light gray, in the drawing lightly shaded), diallage (in the photograph darker gray, in the drawing dark shading), and a little brown hornblende (dotted in diagram), labradorite (white in the photograph, showing twin lamellae in the drawing), and some pyrrhotite (black).

which, in the present case, it is not in parallel growth. This cannot be explained otherwise than that the hypersthene had finished forming before the commencement of crystallization of the diallage.

I believe I am right in drawing the conclusion that when hypersthene and diallage appear together in igneous rocks, the hypersthene, regardless of the quantitative proportion between the two minerals, is prevailingly the oldest. Hypersthene (consisting of two chief components) and diallage (consisting of several

components) are consequently related to each other as the components with high and low melting-points in the binary mix-crystal system No. IV (cf. Fig. 36).

PYROXENE AND BIOTITE, RESPECTIVELY HORNBLENDE, IN THE GABBRO ROCKS

We have previously treated one case, viz., the quartz-norite from Romsaas (see pp. 434–35) where *hypersthene* first crystallized, but later stopped forming as the remainder of the ferromagnesian silicate in the magma entered into *biotite*. In another series of norites and gabbros with relatively much orthorhombic or monoclinic pyroxene and usually with only 2–5, seldom up to 8–10 per cent of biotite, we find the latter (see, for example, Fig. 13) partly grown into the *exterior* parts of, and partly grown on to, the pyroxene, indicating that the biotite belongs to a somewhat later stage of crystallization than the pyroxene.

Primary hornblende is lacking in numerous Norwegian norites and gabbros, but appears in others, most often, however, only in a quantity of 5–10 per cent. This primary hornblende, which always, or nearly always, is brown or greenish-brown, and probably throughout contains some titanic acid, often shows a parallel intergrowth with the orthorhombic or monoclinic pyroxene, in such a manner that the hornblende appears at the periphery of the pyroxene. Or the hornblende may have grown as independent individuals on to the pyroxene. This signifies also for the hornblende a stage of forming later than for the pyroxene. The explanation probably is that the original small contents of H_2O in the gabbroidic magma was concentrated in the residual magma by the solidification of a greater or lesser part of the pyroxene, so that biotite, respectively hornblende, was able to individualize. This will be discussed in a later chapter.

OLIVINE, Mg_2SiO_4:Fe_2SiO_4

The melting-point of pure Mg_2SiO_4, according to the determination at the Geophysical Laboratory, Washington, is 1890°. The melting-point of Fe_2SiO_4 lies, according to approximate determination, at *ca.* 1100°. Doelter gives *ca.* 1065°. Mg_2SiO_4 and Fe_2SiO_4 form a continuous mix-crystal series.

a) As there is such an exceedingly great difference between the melting-points of the two components, it must a priori be taken for granted that the binary system Mg_2SiO_4:Fe_2SiO_4 belongs to type I (without a maximum or minimum).

b) In zonal olivine we find, according to a number of investigators (Sigmund, Becke, Stark),[1] Mg_2SiO_4 concentrated in the

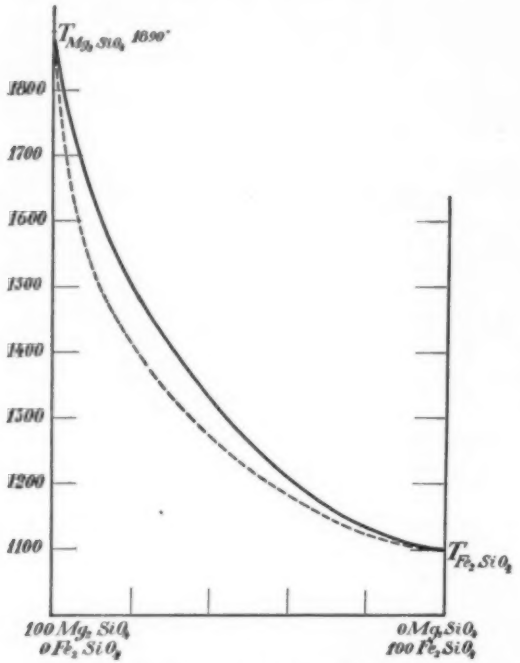

Fig. 22.—Schematic melting-diagram Mg_2SiO_4:Fe_2SiO_4 (percentages by weight)

kernel, and Fe_2SiO_4 in the peripheral zone. Stark found in a zonal olivine from basalt containing 19.5 per cent Fe_2SiO_4 in the kernel and 34.5 per cent in the exterior zone, consequently a marked difference, but not by far so great a difference as between Ab:An in the plagioclase of corresponding rocks. These investi-

[1] See *Tscherm. min. u. petr. Mitt.*, Vols. XVI, XVII, and XVIII.

gations of zonal olivine apply to the common rock-forming olivine, with at most 35–40 per cent Fe_2SiO_4 (and rest Mg_2SiO_4).

c) The earlier approximate determinations, especially by Doelter, show for olivine with increasing percentages of Fe_2SiO_4, continuously decreasing "melting-points" (ɔ:melting-point interval).

d) The later investigations prove *inter alia* that even so small a percentage of Fe_2SiO_4 as 10–15 per cent lowers the melting-point interval of the olivine considerably below the melting-point of Mg_2SiO_4. A maximum of the melting-curve, which in this case must have occurred at predominant Mg_2SiO_4 and little Fe_2SiO_4, is therefore out of the question.

In conformity with all the above observations I believe myself justified in illustrating the binary system Mg_2SiO_4:Fe_2SiO_4 by the foregoing sketch (Fig. 22); it must be emphasized, however, that the course of the curve is only sketched.[1] As the zonal structure of the olivine is far less prominent and there is less difference between the two components than in the plagioclase in rocks with about the same cooling-rate, the difference between the liquidus and solidus curves must be less for Mg_2SiO_4:Fe_2SiO_4 than for An:Ab.

OLIVINE AND PLAGIOCLASE

As explained in my earlier treatise "Die Silikatschmelzlösungen," I and II (1903–4), olivine and anorthite do not crystallize at the pressure of one atmosphere in molten masses of certain intermediate mixtures of Mg_2SiO_4 and $CaAl_2Si_2O_6$, for here new minerals are formed, chiefly melilite and spinel. In conformity with this, in the treatise above cited, I discussed for basic silicate melts with anorthite and olivine as the two extremes, not the individualization boundary between olivine and anorthite, but between (*a*) olivine and melilite, and (*b*) melilite and anorthite.

O. Andersen (at that time with the Geophysical Laboratory, Washington), in his treatise "The System Anorthite:Forsterite:Silica,"[2] arrived at the same results, for by intermediate mixtures of An and Mg_2SiO_4—viz., between 90 An:10 Mg_2SiO_4 and 54 An:46 Mg_2SiO_4—he obtained crystallized spinel. At *high pressure*,

[1] A minimum in the neighborhood of Fe_2SiO_4 is not excluded but very improbable.

[2] *Loc. cit.*

as in the crystallization of deep-seated igneous rocks, we find a different case. *Forellengestein* or troktolite, for instance, consists of very basic plagioclase (anorthite-bytownite) and olivine. Some anorthosites show predominant plagioclase (bytownite, labradorite) and in addition some olivine, and some olivine gabbros consist chiefly of basic plagioclase and olivine with only a small amount of monoclinic or orthorhombic pyroxene. On remelting several of these rocks at atmospheric pressure, more or less melilite results, and in addition frequently some spinel, and occasionally also other minerals. At the pressure of one atmosphere, consequently, quite a different mineral combination results from the magmas here mentioned than the combination occurring in the deep-seated rocks. We shall in a following chapter discuss the cause of this. Here we shall only fix our attention on the fact that the melting of intermediate mixtures of $CaAl_2Si_2O_8$ and Mg_2SiO_4 at the pressure of one atmosphere does not give us the required information of the individualization boundary between plagioclase (anorthite) and olivine, which takes place at high pressure. In the question in hand, therefore, we must use the analytical method.

Petrographical experience shows that the olivine in most of the igneous rocks crystallized at a very early stage. Because of this fact, many petrographers have the conception that olivine takes an exceptional position with regard to the sequence of crystallization and that this mineral always crystallizes as No. I of the silicate minerals. This is, however, a misconception.[1] The reason why the olivine in numerous cases commences crystallizing earlier than the other silicates is that the individualization boundary between olivine and plagioclase or pyroxene, or between olivine and plagioclase plus olivine, lies at the point of relatively little olivine, and that most rocks contain more olivine than the individualization boundary mentioned. But if less olivine is present the solidification commences with the crystallization of one of the other minerals. Returning to the rocks which consist only or nearly only of olivine

[1] As early as in my first mineral-synthetic work ("Studies on Slags," 1885) I opposed this misconception, which *inter alia* also has been expressed in petrographical works of later years. But when a misconception of an authoritative character has been impressed on one's consciousness, it may require a decade of years to uproot it.

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and (basic) plagioclase, it has already been indicated by A. Harker[1] that of these two minerals, the one present in quantity above a certain limit first commences crystallizing. This is also in accordance with my own investigations.

I find it superfluous to discuss the plagioclase rocks with considerable olivine, and as a consequence with crystallization of an

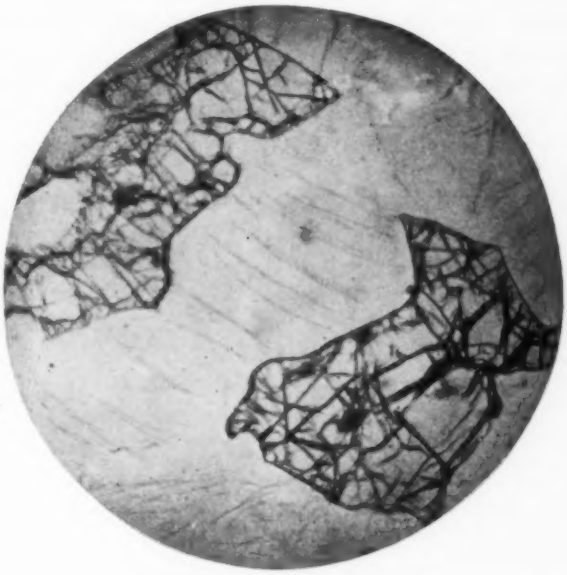


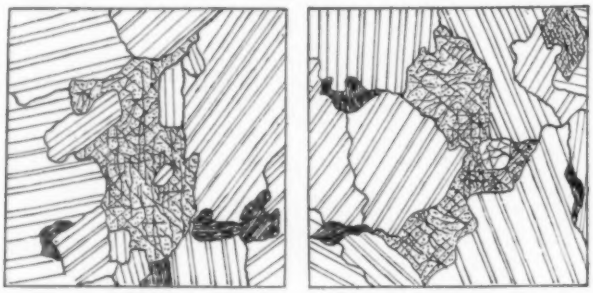
FIG. 23.—Photomicrograph (20:1)

essential part of the olivine before the commencement of the solidification of the plagioclase. But I am going to discuss the inverse proportion, much plagioclase and little olivine, and choose as an example an olivine-bearing labradorite rock from the Ekersund field. This consists of nearly 90 per cent labradorite (Ab_1An_1), about 7 per cent olivine (optically negative; $2V = ca.\ 85°$, consequently with about 0.25 Fe_2SiO_4:0.75 Mg_2SiO_4), besides a little diallage. (See photograph Fig. 23 and drawing Fig. 24.)

[1] *The Natural History of Igneous Rocks*, 1909, p. 170.

The olivine here shows no sign of idiomorphism, but this is often the case with labradorite. Laths (parallel to 010) of the latter here and there (Fig. 24*a*) protrude into the olivine, and the straight-edged boundary which we often observe (Fig. 23) between the labradorite and the olivine is not caused by the crystal-limit of the olivine, but by that of the plagioclase. The feldspar must thus here have commenced crystallizing at an earlier stage than the olivine, which, in the same manner as the diallage in Figures 24*a* and 24*b*, and as the hypersthene in Figure 14, chiefly forms an intervening mass between relatively large labradorite individuals.

In the *olivine-rich olivine hyperites* (hyperitic-structured olivine gabbros) with about 25–30 per cent olivine, 60 per cent



a *b*

FIGS. 24*a* and 24*b*.—Drawings (20:1)

Anorthosite from Ekersund, Norway, containing *ca.* 90 per cent labradorite (Ab_1An_1), *ca.* 7 per cent olivine (dotted in Fig. 24), and a little diallage (dark shading in Fig. 24, not seen in the photograph). The straight lines in Figure 23 represent the idiomorphic contours of the labradorite against the olivine.

labradorite, 10–20 per cent diallage, and a little magnetite, etc., the olivine chiefly appears in synneutic individuals with very good idiomorphism against the diallage and partial idiomorphism also against the plagioclase (see, for instance, Fig. 33). Considering only the silicate minerals, we find consequently that first a good deal of olivine solidified, then the labradorite, and at a later stage the diallage also commenced crystallizing.

In the *olivine-poor olivine hyperites*, with only 5–10 per cent olivine, we find, on the other hand, in the relation between the olivine and the labradorite quite a different structural phenome-

non, viz., lath-shaped labradorite individuals protruding into the olivine, and the latter shows no sign of idiomorphism even against the labradorite. The olivine chiefly fills the intervening spaces between the plagioclase laths in the same manner as in the anorthosite illustrated in Figures 23 and 24. We refer, for instance, to Figures 48 and 49 where the original structure, however, is partly effaced by the here quite strongly developed reaction rims between the olivine and the labradorite. In these olivine-poor olivine hyperites a greater or lesser part of the plagioclase must according to the structure have crystallized earlier than the olivine.

On the basis of the crystallization sequence we draw the conclusion that the individualization boundary at high pressure between the olivine (about $1Fe_2SiO_4 \cdot 2Mg_2SiO_4$) and basic plagioclase lies at little olivine and much plagioclase. As an estimate we may set the individualization boundary (by weight) at 0.15 Oliv.:0.85 Ab_1An_1, 0.25 Oliv.:0.75 Ab_1An_3, and probably about 0.35 Oliv.:0.65 An. That these statements are approximately right is verified by a study of the "orbicular gabbro" from Debesa, California, described by A. C. Lawson,[1] which carries orbs with changing shells (challotes) of radially arranged olivine together with bytownite. This structure must depend on a *simultaneous* crystallization of the two minerals, that is to say, a crystallization along a eutectic boundary-line. From the quantitative analysis we calculate the composition of this boundary at about 0.34 Oliv. (0.35 Fe_2SiO_4. 0.65 Mg_2SiO_4):0.66 Plag. ($Ab_{16}An_{84}$, consequently about Ab_1An_5.)

The quartary system $Ab:An:Mg_2SiO_4:Fe_2SiO_4$ separates at high pressure into two individualization fields, viz., Ab+An and $Mg_2SiO_4+Fe_2SiO_4$. We may here apply the same general considerations as for the system Ab+An and $CaMgSi_2O_6+CaFeSi_2O_6$ (see p. 442).

OLIVINE AND PYROXENE

Olivine and monoclinic pyroxene.—Forsterite, Mg_2SiO_4 (melting-point = 1890°) and diopside, $CaMgSi_2O_6$ (melting-point = 1391°), form, according to N. L. Bowen,[2] a eutectic, 88 per cent diopside: 12 per cent forsterite with melting-point = 1386°, consequently

[1] *Univ. of Cal. Publications, Dept. of Geol.*, Vol. III (1904).

[2] "The Ternary System Diopside-Forsterite-Silica," *Amer. Jour. of Sci.*, Vol. XXXVIII (1914).

only 4–5° below the melting-point of diopside. According to my earlier studies on slags, the individualization boundary between augite ($CaMgSi_2O_6$ with some $CaFeSi_2O_6$, $MgAl_2SiO_6$, etc.) and olivine (Mg_2SiO_4 with some Fe_2SiO_4 and Mn_2SiO_4, consequently with a much lower melting-point than pure Mg_2SiO_4) lies at about 70 per cent of augite:30 per cent of olivine. At this individualization boundary a decrease of the melting-point appears according to experimental investigations.[1] We accordingly here have to deal with a eutectic boundary-line between the two mix-crystals. The location of this boundary is chiefly dependent upon the composition of the olivine, and this is probably due to the fact that the melting-point interval of the olivine is considerably lowered by some Fe_2SiO_4. (See Fig. 22.)

Regarding Mg_2SiO_4:$MgSiO_3$, and especially with regard to the dissociation of $MgSiO_3$ at the pressure of one atmosphere and at high temperature (1577–1555°), some forsterite first being solidified from melted $MgSiO_3$, we refer to Bowen's investigations which are discussed in a following chapter. I here arrive at the result that the dissociation of $MgSiO_3$, determined at the pressure of one atmosphere, cannot be transferred to apply to (Mg, *Fe*) SiO_3 or (Mg, Fe) SiO_3 at *high* pressure.

In igneous rocks consisting of olivine and orthorhombic or monoclinic pyroxene, the olivine chiefly appears in idiomorphic individuals when the olivine forms at least one-third, and the pyroxene at most two-thirds. This fact is so well known that I find it superfluous to give special examples. But when the olivine is present only in small quantity, the sequence of crystallization is quite turned about. Such rocks, with predominant pyroxene and quite little olivine, are in themselves rare, and furthermore the olivine in these rare rocks is only exceptionally fresh enough to permit a detailed study of the original structure of the rock. As far as I know, these rocks have not previously attracted any special attention; I shall therefore discuss a couple of examples.

In a hypersthenite-norite from Nonaas-Litland in Hosanger, Norway (see analysis in the chapter on norites in Part II), a con-

[1] See "Silikatschmelzlös.," II.

cretion of an *olivine-bearing hypersthenite* (or olivine-augite-hornblende-hypersthenite) appears locally (at Nonaas), with a chemical composition:

about 47–48 per cent SiO_2
about 0.5–1 per cent TiO_2
about 5–6 per cent Al_2O_3
about 2.5–3 per cent Fe_2O_3
about 12–13 per cent FeO
about 17–18 per cent MgO
about 11–12 per cent CaO
about 0.5–1 per cent alkali

This rock, which is quite fresh, consists mineralogically of about 75 per cent pyroxene, viz., about 50 per cent hypersthene (optically negative, $2V = ca.\ 80°$, that is to say, with stoechiometric 25–30, closest at about 27 per cent $FeSiO_3$) and about 25 per cent monoclinic pyroxene (extinction-angle 39–40°); on an average about 12 per cent olivine (optically negative, $2V = ca.\ 83°$, consequently with stoechiometric[1] about 30 per cent Fe_2SiO_4); about 12 per cent intensively greenish-brown, primary hornblende; and in addition locally 0.5 per cent biotite and about 0.5 per cent plagioclase, the latter only here and there as mesostasis of quite subordinate importance. Oxidic iron ore is entirely lacking. Apatite and pyrites appear in small quantity. On the photomicrograph, Figure 25, the light-streaked mineral chiefly consists of hypersthene and a few individuals of monoclinic pyroxene. Uppermost to the right we see a hypersthene individual, cut at right angle to the *c*-axis.

The mineral which on account of the strong absorption of light shows dark-gray in the photograph is hornblende, and the mineral which appears white is olivine, quite fresh, without any sign of serpentinization or other change. The pyroxene individuals show, as well in length as in cross-section, quite good idiomorphism against the olivine. The same, though not quite so distinctly, is the case with the hornblende, which belongs to a somewhat later stage of crystallization than the hypersthene (see above). On the other hand, the olivine does not show even a sign of idiomorphism against the hypersthene and the other minerals, but forms—in

[1] The optical determinations have been undertaken by Docent Carstens and myself in collaboration.

the same manner as the plagioclase in the gabbro rocks which are especially rich in hypersthene or diallage—a mass of putty or a *Zwischenklemmungsmasse* (mesostasis) between the ferromagnesian silicate minerals.

So we arrive at the result that in the rock in question, with little olivine and predominant hypersthene, with monoclinic pyroxene and some hornblende, the olivine belongs to the *last* stage of crystallization.

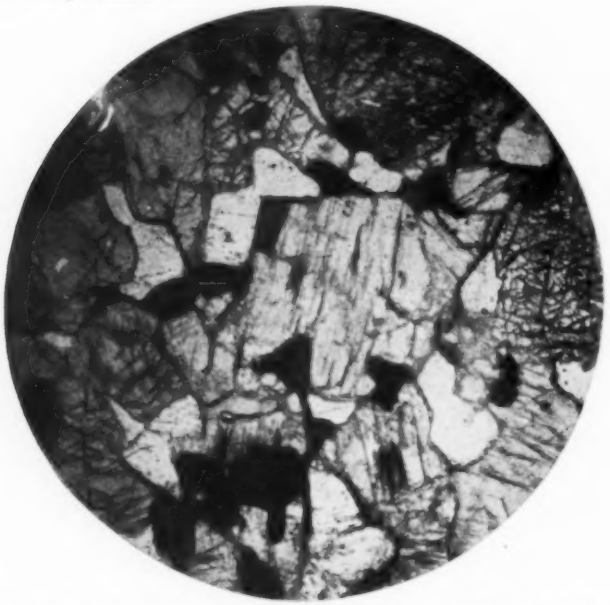


FIG. 25.—Photomicrograph (24:1) of olivine-bearing hypersthenite with some diallage and hornblende, from Nonaas, Hosanger, Norway. The light-gray mineral is hypersthene with some diallage, the dark-gray is hornblende, and the white olivine.

Also in some other olivine-bearing pyroxenites, moderately rich in iron, with predominant hypersthene, or diallage or both, and in addition with only a quite small amount, say 10 or 15 per cent, of olivine, the structure proves the late commencement of the crystallization of the olivine.

If we pass on to the dunites and saxonites *poor in iron*, usually with 40–43 per cent SiO_2, 42–48 MgO, 7–10 FeO, 0–1.5 CaO, and

a little Al_2O_3, we find that the dunites consist nearly exclusively of olivine, and the saxonites usually of predominant olivine with only quite little bronzite or enstatite-bronzite.

Olivine-bronzite (or enstatite) rocks with predominant orthopyroxene and quite little olivine are very rare, and personally I have only once (1893) found such a rock, viz., as a local facies of a peridotite at Esjeholmen near Næsö, in the Hestmandö district, near the Polar Circle in the northern part of Norway.[1]

As illustrated in Figure 26, there here appear rosettes of radially arranged bars of enstatite which in most places are entirely unchanged, but in some places somewhat altered to tremolite, clinochlorite, talc, and magnesite.

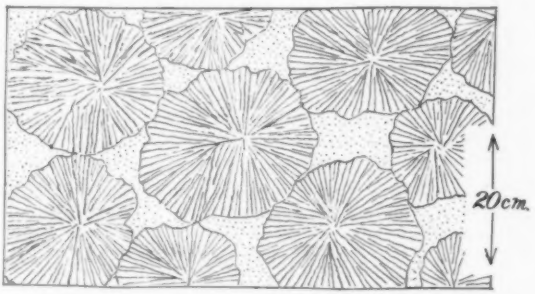


FIG. 26.—Enstatite-olivine rock from Esjeholmen, near Næsö, Hestmandö district, northern Norway. Contains great rosettes of enstatite and an intervening mass of olivine with some enstatite. (1/10 nat. size.)

The bars of enstatite in these rosettes may reach a length of 1 dm., or somewhat more, and the enstatite rosettes may have the size of the head of a full-grown man. The intervening mass between the enstatite rosettes consists of olivine and enstatite. In the entire rock we may reckon about 80 per cent enstatite rosettes and only about 20 per cent intervening mass, consequently for the whole rock about 90 per cent enstatite and 10 per cent olivine, in addition to a minimal quantity of chromite. I cannot explain this structure otherwise than that at first the enstatite of the large rosettes was formed, and later the intervening mass, consisting of olivine and enstatite. The result of this is that the sequence of

[1] See a treatise by myself in *Zeitschr. f. prakt. Geol.*, 1894, pp. 389–92, and a treatise by C. W. Carstens, "Norske peridotiter," I, *Norsk geol. tidskr.*, Vol. V (1918).

crystallization in the deep-seated rocks of olivine and monoclinic, or orthorhombic, pyroxene must be explained by the same laws as for the other ordinary rock-forming minerals, and that the individualization boundary lies at predominant pyroxene:little olivine.

ON THE RELATION BETWEEN MgO AND FeO (OR BETWEEN Mg-SILICATE AND Fe-SILICATE) IN THE FERROMAGNESIAN SILICATES, CRYSTALLIZED FROM THE SAME MAGMA

We include a selection of analyses of the primary ferromagnesian minerals appearing in the same rock:

	No.	SiO_2	TiO_2	Cr_2O_3	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	Total
	Websterite (No. 49) with Bronzite (*b*) and Diopside (*c*)														
Websterite	49	52.55	0.14	0.44	2.71	1.27	4.90	0.24	20.39	16.52	0.27		Tr.	1.09	100.52
Bronzite	*b*	54.53	.....	0.30	1.93	1.70	8.92	0.28	29.51	2.25	.....	.....	.....	1.14	100.56
Diopside	*c*	51.80	0.13	0.51	2.21	1.29	3.50	Tr.	17.76	20.99	.....	.....	.....	0.65	98.84
	Pikrite (No. 50) with Bronzite (*b*) and Diopside (*c*)														
Pikrite	50	37.12	0.40	.....	4.96	8.92	7.62	0.40	26.92	6.14	0.40	0.49	0.10	5.04	98.60
Bronzite	*b*	54.20	.....	0.29	2.05	.....	10.08	.....	29.00	2.49	.....	.....	.....	0.42	98.53
Diopside	*c*	52.63	.....	0.72	2.24	.....	6.84	.....	17.30	20.04	.....	.....	.....	0.57	100.34
	Hypersthene Diabase (No. 51) with Hypersthene (*b*) and Augite (*c*)														
Diabase	51	50.86	.....	.....	7.95	.....	7.41	.....	18.93	13.29	1.34	0.20	.....	.....	100.00
Hypersthene	*b*	52.16	.....	.....	3.00	0.43	15.16	0.36	21.89	5.04	0.16	0.04	.....	0.08	99.24
Augite	*c*	49.33	.....	.....	9.15	0.27	9.05	.....	14.58	16.36	0.55	0.19	.....	0.25	99.73
	Diallage-Hornblende-Gabbro (No. 52) with Diallage (*e*) and Brown, Primary Hornblende (*d*)														
Gabbro	52	53.19	0.25	.....	11.42	1.74	8.15	0.17	10.84	11.01	2.97	0.31	.....	.....	100.05
Diallage	*e*	51.23	0.86	.....	2.75	3.88	14.09	Tr.	17.05	9.74	.....	.....	.....	1.75	101.35
Hornblende	*d*	48.04	.....	.....	8.98		16.44	.....	18.87	6.72	.....	.....	.....	.....	99.06
	Dacite (No. 53) with Hypersthene (*b*), Biotite (*e*), and Ilmenite (*f*)														
Dacite	53	63.27	1.30	.....	16.50	0.68	5.10	0.03	2.48	4.18	2.36	2.68	0.15	0.61	99.50
Hypersthene	*b*	50.42	3.51	.....	4.06	2.10	23.54	0.24	13.01	1.30	Tr.	0.69	0.92	0.16	99.98
Biotite	*e*	39.86	7.95	.....	11.13	1.39	18.10	0.58	9.88	Tr.	0.35	6.73	.....	3.63	99.60
Ilmenite	*f*	.....	67.28	.....	.....	.....	31.92	.....	0.80	.....	.....	.....	.....	.....	100.00
	Peridotite (No. 54, Kimberlite, Strongly Decomposed) with Olivine (*g*), Garnet (*h*), and Ilmenite (*f*)														
Peridotite	54	29.81	2.20	0.43	2.01	5.16	4.35	0.23	32.41	7.69	0.11	0.20	0.35	8.92	100.86
Olivine	*g*	40.04	0.07	0.24	0.39	2.36	7.14	0.20	46.68	1.16	0.08	0.21	0.04	0.80	99.42
Garnet	*h*	41.32	0.16	0.91	21.21	4.21	7.93	0.34	19.32	4.94	0.07	.....	.....	0.17	100.58
Ilmenite	*f*	0.76	49.32	0.74	2.84	9.13	27.81	0.20	8.68	0.23	0.19	.....	.....	0.20	100.00

No. 49: Websterite, composed only of bronzite and diallage. Hebbville near Baltimore. G. H. Williams, *Amer. Geologist*, Vol. VI; F. W. Clarke, *U.S. Geol. Sur. Bull. 228* (1904), p. 51.—No. 50: Pikrite. Schwarzenstein, Fichtelgebirge. In the rock 0.09 per cent CO_2. Gümbel, *Geogr. Beschreibung Bayerns*, 1879. (Rosenbusch, *Gesteinslehre*, p. 352.)—No. 51: Hypersthene diabase. Twins by Rapidan, Virginia. Campbell and Brown, *Bull. Geol. Soc. Am.*, II.—No. 52: Diallage-hornblende-gabbro. Veltein, in the Alps. Küchler, *Chemie der Erde*, I, 1914. The analysis of the rock from Hecker, *Neues Jahrb. f. Min., Geol. u. Pal.*, Beil., Bd. XVII (1903).—No. 53: Hypersthene-biotite-dacite. Upway, Victoria. Skeats, *Quart. Jour. Geol. Soc. London*, 1910. In the rock 0.16 per cent S. In the biotite H_2O+, 3.20 and $H_2O\div$, 0.43 per cent.—No. 54: Kimberlite, strongly decomposed. From Elliot County, Kentucky. In the rock 8.92 per cent H_2O, 6.66 CO_2, 0.28 SO_3, 0.05 NiO. Diller, *U.S. Geol. Soc. Bull. 38*, and *Amer. Jour. Sci.*, 3d Series, Vol. XXXII; Clarke, *U.S. Geol. Soc. Bull. 228*, p. 66.

OLIVINE AND ORTHORHOMBIC PYROXENE

We shall commence with some analyses of olivine and bronzite from olivine nodules in basalts. We shall base the calculations for the bronzite, often somewhat decomposed, on the entire quantity of iron found analytically. In reality a little, but only very little, iron in the bronzite will appear as Fe_2O_3.

The stoechiometric relation between MgO and FeO in olivine and bronzite for olivine nodules:

Styria. (Kappenstein, etc.)....	55*a*	Olivine	1 MgO:0.11 FeO
	55*b*	Bronzite	1 MgO:0.14 FeO
	56*a*	Olivine	1 MgO:0.11 FeO
	56*b*	Bronzite	1 MgO:0.10 FeO
Dreizer Weiher, Eifel....	57*a*	Olivine	1 MgO:0.09 FeO
	57*b*	Bronzite	1 MgO:0.11 FeO
	58*a*	Olivine	1 MgO:0.11 FeO
	58*b*	Bronzite	1 MgO:0.10 FeO
Stempel, Marburg	59*a*	Olivine	1 MgO:0.10 FeO
	59*b*	Bronzite	1 MgO:0.11 FeO
Kaiserstuhl, Baden	60*a*	Olivine	1 MgO:0.09 FeO
	60*b*	Bronzite	1 MgO:0.10 FeO
Reihenweiler, Alsace	61*a*	Olivine	1 MgO:0.14 FeO
	61*b*	Bronzite	1 MgO:0.14 FeO

Nos. 55*a*, *b*, and *c*: Kukurzenkezel near Kappenstein: Schadler, *Tscherm. Mitt.*, Vol. XXXII (1914).—No. 56*a* and *b*: Schiller, Becke, *Tscherm. Mitt.*, Vol. XXIV.—Nos. 57*a* and *b*: Th. Kierulf, *Bischof's chem. Geol.*, and *Pogg.*

Ann., Vol. CXLI.—Nos. 58*a*, *b*, and *c*: Philipp, *Neues Jahrb. f. Min.*, etc., 1871, and Rammelsberg, *Pogg. Ann.*, Vol. CXLI.—Nos. 59*a*, *b*, and *c*: Bauer, *Neues Jahrb. f. Min.*, etc., 1891, II.—Nos. 60*a* and *b*: Knop, *Neues Jahrb. f. Min.*, etc., 1877.—Nos. 61*a* and *b*: Linck, *Zeitschr. f. Kryst. u. Min.*, Vol. XVIII.

The value of FeO in the bronzite should be reduced a little throughout, probably about one-tenth in most cases.

Joh. Schiller has discussed the question in hand in a special treatise,[1] partly on the basis of several of the analyses here given of olivine nodules in basalts, and partly on the determination of the chemical composition of the two minerals on the basis of the axial angle and optical character. He comes to the result that MgO and FeO in the feldspar-free rocks are quite evenly distributed in the olivine and orthorhombic pyroxene, and this conclusion is confirmed by my own investigations. But with regard to the rocks containing feldspar he supposes a relative, sometimes even a relatively extensive, enrichment of MgO in the olivine. The observations on which he bases this last construction, however, are few, and in my opinion rather dubious.[2]

Olivine and orthopyroxene,[3] isolated from a series of peridotites poor in iron (saxonites, olivine-schists, etc.) with only very little Al_2O_3, Fe_2O_3, and CaO, show:

Olivine, 1 MgO:0.08, 0.08, 0.08, 0.10, 0.11 FeO;
Orthopyroxene, 1 MgO:0.07, 0.07, 0.07, 0.10, 0.12, 0.12, FeO.

In peridotites, a little richer in iron, and at the same time carrying somewhat more Al_2O_3, Fe_2O_3, and CaO, we find:

Olivine, 1 MgO:0.15, 0.21 FeO;
Orthopyroxene, 1 MgO:0.13, 0.15, 0.16 FeO.

As well with regard to the short report above as to Schiller's investigations, MgO and FeO in the feldspar-free rocks in question are quite evenly divided between the two minerals. The various lesser differences—which would indicate a small relative enrichment

[1] *Tscherm. Mitt.*, Vol. XXIV (1905).

[2] Especially for the extremely low FeO-contents in olivine from an olivine-gabbro from Tilai, Ural.

[3] Enstatite-bronzite-hypersthene deserves, in the same manner as anorthite-bytownite-labradorite-andesine-oligoclase-albite, a common term, and as such I will use "orthopyroxene," that is to say, pyroxene belonging to the orthorhombic system. I believe I occasionally have heard or read this term before, so the proposition is not originally mine.

of MgO in the olivine in some cases, and in the orthopyroxene in others—approximately balance, and probably depend chiefly on the source of errors connected with the determinations.

If we pass on to the *gabbroidic* rocks, we find that hypersthene, in the common anchi-eutectic norites, usually shows—as well on the basis of the analysis of isolated hypersthene, as by the determinations of the axial angle undertaken by earlier investigators and by myself—a composition between about 30 and 38–40 per cent $FeSiO_3$ (stoechiometric). And the olivine shows, as well on the basis of the analyses of isolated material, as on my own determinations of the axial angle, about 32–35 per cent Fe_2SiO_4.

In the hypersthenite-norites (with only relatively little plagioclase) we usually find, however, a relatively lower percentage of iron, as well in the rock as in the separated silicate minerals. This is discussed more elaborately in Part II. We shall include a couple of separate determinations: The thin secretion of a hypersthenite-norite, above mentioned (Fig. 25), consisting chiefly of hypersthene, augite, hornblende, and olivine shows:

Hypersthene, optically negative, $2V = ca.\ 80°$, gives 25–30 (about 27) per cent $FeSiO_3$;

Olivine, optically negative, $2V = ca.\ 83°$, gives about 30 per cent Fe_2SiO_4.

Olivine-carrying norite with only about 40 per cent labradorite from Skjækerdalen (Figs. 20–21):

Hypersthene, optically negative, $2V = ca.\ 80–85°$, gives about 25 per cent $FeSiO_3$;

Olivine, optically negative, $2V = ca.\ 85–88°$, gives 20–25 per cent Fe_2SiO_4.

Also in the igneous rocks containing feldspar, we find approximately the same MgO:FeO proportion in both minerals. Any relative enrichment of MgO in the olivine is usually not to be found.

ORTHORHOMBIC AND MONOCLINIC PYROXENE

As special Fe_2O_3 determinations are lacking in several cases and in others are little instructive on account of a later oxidation, we in both minerals originate from the entire percentage of iron, this giving a quite true image of the relative proportions of MgO and FeO in the two minerals. On account of the small percentage of Fe_2O_3 the statements for FeO ought, however, for the

orthorhombic pyroxene to be reduced about one-tenth, and for the monoclinic pyroxene, which throughout contains a little more Fe_2O_3, about one-eighth. This correction, however, is of small extent.

The stoechiometric proportion between MgO and FeO in orthorhombic and monoclinic pyroxene from the same rock:

Olivine nodules from basalts	Marburg	59*b*	Bronzite	1 MgO:0.11 FeO
		59*c*	Diopside	1 MgO:0.07 FeO
	Dreizer Weiher	58*b*	Bronzite	1 MgO:0.11 FeO
		58*c*	Diopside	1 MgO:0.14 FeO
	Kaiserstuhl	60*b*	Bronzite	1 MgO:0.10 FeO
		60*c*	Diopside	1 MgO:0.16 FeO
	Kappenstein	55*b*	Bronzite	1 MgO:0.14 FeO
		55*c*	Diopside	1 MgO:0.18 FeO
Websterite		49*b*	Bronzite	1 MgO:0.20 FeO
		49*c*	Diopside	1 MgO:0.15 FeO
Pikrite		50*b*	Bronzite	1 MgO:0.20 FeO
		50*c*	Diopside	1 MgO:0.22 FeO
Hypersthene Diabase		51*b*	Hypersthene	1 MgO:0.40 FeO
		51*c*	Augite	1 MgO:0.35 FeO

If we deduct the small, analytically found figures for Fe_2O_3 from the last rock (No. 51), we have:

Hypersthene, No. 51*b*, 1 MgO : 0.39 FeO;
Augite, No. 51*c*, 1 MgO : 0.35 FeO.

The seven double analyses of orthorhombic and monoclinic pyroxene give approximately the same proportions between MgO and FeO, in some cases a little difference in one, and in some in the other direction, but there is no particularly constant enrichment of one component in either of the two minerals. A series of analyses shows that where orthorhombic and monoclinic pyroxene appear as primary formations in the same rock, the monoclinic is characterized by a somewhat higher percentage of TiO_2, Cr_2O_3, Al_2O_3 —and probably also of Fe_2O_3—than the orthorhombic.

DIALLAGE AND PRIMARY BROWN HORNBLENDE

Küchler's two analyses from a diallage-hornblende gabbro (No. 52) show, the total quantity of iron being reckoned as FeO:

Diallage, No. 52*c*, 1 MgO : 0.57 FeO;
Hornblende, No. 52*d*, 1 MgO : 0.48 FeO.

If we deduct 3.88 per cent Fe_2O_3 in the diallage and, at an estimate, 2.0 per cent Fe_2O_3 in the hornblende, we get:

Diallage, No. 52*c*, 1 MgO : 0.46 FeO;
Hornblende, No. 52*d*, 1 MgO : 0.42 FeO,

consequently, as emphasized by Küchler, about the same MgO: FeO proportion in both minerals.

HYPERSTHENE AND BIOTITE

The two analyses from a dacite (No. 53) show:

Hypersthene, No. 53*b*, 1 MgO : 1.00 FeO;
Biotite, No. 53*e*, 1 MgO : 1.02 FeO,

consequently exactly the same MgO:FeO proportion in both minerals.

If for the Romsaas quartz-orbicular-norite, which in the entire rock only contains about 0.5 per cent Fe_2O_3, we assume as an estimate 1 per cent Fe_2O_3 in the biotite, we get:

Hypersthene, No. 41, 1 MgO : 0.39 FeO;
Biotite, No. 42, 1 MgO : *0.27 FeO.*

Even if the last figure is not quite exact, relatively somewhat less FeO appears in the biotite than in the hypersthene.

When there is a simultaneous appearance of biotite and hypersthene in the same rock, the biotite seems throughout to carry considerably more TiO_2 than the hypersthene.

The summary, here briefly stated, verifies the earlier conclusion, especially by A. Merian[1] (1884), W. Wahl[2] (1906), and Küchler (*loc. cit.*, 1914), viz., that the composition of the ferromagnesian silicates depends quite simply upon the composition of the entire rock or magma, and further that the relations between MgO and FeO (or Mg-and Fe-silicate) in two from the same magma crystallizing ferromagnesian silicates such as olivine:orthorhombic

[1] "Analysen gesteinsbildender Pyroxene," *Neues Jahrb. f. Min.*, etc., Beil., Bd. III (1884).

[2] *Die Enstatitaugite* (dissertation), Helsingfors, 1906; *Tscherm. Mitt.*, Vol. XXVI (1907).

pyroxene, orthorhombic:monoclinic pyroxene, diallage:primary hornblende, hypersthene:biotite, are not subject to extensive variations. We may find a little variation sometimes in one and sometimes in the other direction, but this may be due in part to inaccurate determinations. But all in all, we here have approximately the same MgO:FeO proportions in both minerals. We especially emphasize that no mineral is characterized by a constant relative enrichment either of MgO or FeO. Lesser variations, with regard to the MgO:FeO proportion, by two or still more ferromagnesian silicates, crystallizing from the same magma, may be due to a series of factors, of which we may mention the horizontal distance between the liquidus and solidus curves (or the difference between the a:b proportion in the first crystallized mix-crystal and in the liquid phase); the degree of equilibrium between the solid and liquid phases; the electrolytic dissociation.

A *small* horizontal difference between the liquidus and solidus curves, and a nearly complete equilibrium between the solid and liquid phases will cause nearly the same MgO:FeO proportion between the segregated ferromagnesian silicates and the magma, and consequently also between the ferromagnesian silicates mutually.

As well in olivine as in orthopyroxene and diopside-hedenbergite, the Mg-silicate is concentrated in the first mix-crystal. By more or less incomplete equilibrium between the liquid and solid phases—as in the dike and effusive rocks—we may expect a relative enrichment of MgO in the mineral which first commenced crystallizing. With two ferromagnesian silicates we may generally expect a more evenly distributed MgO:FeO proportion among deep-seated rocks with complete or nearly complete equilibrium between liquid and solid phases than among dike and effusive rocks.

Addition.—Also in *ilmenite* a little MgO enters, viz., as $MgTiO_3$. In this manner ilmenite No. 54*f* from a peridotite (with about 0.12 FeO:0.88 MgO in the entire rock) shows not less than 8.68 per cent MgO, or 0.64 FeO:0.36 MgO. The ilmenite from the labradorite rock near Ekersund (with about 0.5 FeO:0.5 MgO

in the entire rock) usually contains 3 to 4, up to 5.14 per cent MgO (the last analysis equivalent to 0.78 FeO:0.22 MgO). In the dacite No. 53, with 0.53 FeO:0.47 MgO in the whole rock, the hypersthene as well as the biotite carries almost exactly 0.50 FeO:0.50 MgO and the ilmenite 0.96 FeO:0.04 MgO.

The proportions of FeO and MgO in the ilmenite, from observation of the three rocks just mentioned, must be a function of the FeO:MgO proportion in the entire rock or in the original magma, but in such a manner that the ilmenite throughout shows a very extensive relative enrichment of FeO (as $FeTiO_3$) and consequently vice versa an extensive, relative decrease of MgO (as $MgTiO_3$).

[*To be continued*]

CYCLES OF EROSION IN THE PIEDMONT PROVINCE OF PENNSYLVANIA[1]

F. BASCOM
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Since 1912, when Professor Barrell brought to the attention of the Geological Society of America some conclusions opposed to the earlier interpretation of the erosion history of certain portions of the Appalachian highlands, the writer has had in mind the possible application of similar conclusions to the erosion history of the Piedmont province of Pennsylvania. The results of this intention are presented in this paper. The conclusions reached are not precisely in accord with those enforced with so much originality by Professor Barrell, nor do they involve much that is new in the interpretation of the erosion history of eastern Pennsylvania, but they are presented as a record of the present stage of the study of the peneplains of the Piedmont province of Pennsylvania.

It is the purpose of the paper to call attention to the fact that the erosion history of eastern Pennsylvania as indicated by altitudes and by the record of sedimentation must have been complex, that it was made up not of one or two or three cycles of prolonged erosion, but of many interrupted cycles, and that vestiges of nine of these cycles testify to their reality. Other cycles may have existed and probably did exist, but too briefly for permanent record. Six of these nine cycles are thought to belong to post-Cretaceous time and three to Cretaceous time.

The question of the subaerial or marine origin of these peneplains is debated, but decisive criteria are lacking for a final pronouncement.

[1] Published by permission of the Director of the United States Geological Survey. The writer takes pleasure in acknowledging her indebtedness to M. R. Campbell and G. W. Stose of the United States Geological Survey for helpful comments and queries made on the subject-matter of this paper, and to Professor W. M. Davis for valuable specific suggestions.

In any investigation of the cycles of erosion, complete or incomplete, that collectively constitute the erosion history of the Piedmont province of the Appalachian highlands, the stratigraphic record preserved on the margin of the province must furnish the data by which the succession and age of such erosion cycles stand or fall.

That aerial and marine erosion has taken place ever since continental plateaus and oceanic basins came into existence is unquestioned: only such interaction of air, water, and land masses is conceivable. The character and rapidity of erosion will be controlled by altitude, rock, and climate, but the duration of an erosion period will be dependent upon the stability of the strand line: a long period of quiescence will permit prolonged aerial and marine erosion with reference to a given base-level, and a period of uplift will interrupt and renew erosion with reference to a new base-level. The evidence of such movements of the strand line inaugurating erosion is furnished by the stratigraphic register.

In the Piedmont province of Pennsylvania with the beginning of Cretaceous sedimentation the stratigraphic record seems to indicate a succession of such erosional conditions maintained by an alternation of periods of continental quiescence with periods of movement. That these periods of stability have been of different durations is an obvious deduction from the sedimentary record.

The stratigraphic record on the Atlantic plain which is the submerged margin of the Piedmont province is as follows:

Recent deposits
Unconformity
Pleistocene deposits
Talbot (Cape May): clay, sand, and gravel.....30 feet
Unconformity
Wicomico (Pensauken): clay, sand, and gravel.....25 feet
Unconformity
Sunderland (Bridgeton): clay, sand, and gravel.....25 feet
Unconformity
Late Brandywine: sand and gravel.....1± foot
Pleistocene (or Late Tertiary?) deposits
Unconformity?
Early Brandywine: sand and gravel.....50 feet

Miocene deposits
- Unconformity
- St. Mary's: sand and clay ..... 280 feet
- Choptank: sand, clay, and marl ..... 175 feet
- Unconformity
- Calvert: sand and clay ..... 310 feet
- Unconformity

Eocene deposits
- Nanjemoy: sand ..... 125 feet
- Aquia: greensand ..... 100 feet
- Unconformity

Upper Cretaceous (Cretaceous) deposits
- Manasquan: clay and sand ..... 50 feet
- Rancocas: greensand ..... 80 feet
- Monmouth: sand ..... 100 feet
- Unconformity
- Matawan: micaceous sandy clay ..... 70 feet
- Unconformity
- Magothy: sand and clay ..... 100 feet
- Unconformity
- Raritan: clay and sand ..... 350 feet
- Unconformity

Lower Cretaceous (Comanchean) deposits
- Arundel: clay and sand ..... 125 feet
- Unconformity
- Patapsco: clay and sand ..... 200 feet
- Unconformity
- Patuxent: sand and arkose ..... 350 feet
- Unconformity
- Crystalline formations

With the Cretaceous, Tertiary, and Pleistocene registration of continental movements before us, it is no longer possible to believe that the erosion history of this region is told in two cycles of erosion, producing two peneplains: the Kittatinny,[1] or Schooley, of Cretaceous age, and the Shenandoah, or Somerville,[2] of Tertiary age. That there is topographic evidence of more than two erosion

[1] Bailey Willis, "The Northern Appalachians," *Nat. Geog. Mon.*, 1895, pp. 169–202. C. W. Hayes, "The Southern Appalachians," *Nat. Geog. Mon.*, 1895, pp. 305–36. C. W. Hayes and M. R. Campbell, "Geomorphology of the Southern Appalachians," *Nat. Geog. Mon.*, 1894, pp. 63–126.

[2] W. M. Davis and J. W. Wood, Jr., "The Geographic Development of Northern New Jersey," *Proc. Bost. Soc. of Nat. Hist.*, Vol. XXIV (1889), pp. 365–423.

periods in the Appalachian highlands has been recognized by Keith,[1] Campbell,[2] and others.

In the sedimentary sequence of the Atlantic plain there are ten significant unconformities—that is, ten intervals of erosion alternating with intervals of deposition. Not all of the deposits are known to be marine, so that ten submergences cannot be postulated. There are six less significant unconformities.

The time represented by the deposits and unconformities has been estimated at 56,500,000 years.[3] There could not conceivably be conditions more favorable for a succession of erosion cycles falling so far short of completion as to leave permanent traces of the sequence, nor a stratigraphic record more compelling for the acceptance of such traces as evidences of erosion cycles. It is not probable that traces are preserved of every incomplete erosion cycle.

The topography of erosion cycles early interrupted would be obliterated by subsequent erosion cycles of longer duration. Small beginnings, if they existed, might be quite similar to the three most recent terraces, which are being modified and will in time be completely obliterated by subsequent erosion.

Such incomplete, obliterated cycles may be registered only in the lesser unconformities of the stratigraphic record, which is easily more complete than the topographic record. Did the geologist base his expectations on stratigraphy alone, he would look for a series of more or less discontinuous and more or less warped benches or terraces facing the sea, or, in the case of the lower terraces, following inland the river valleys, and not perfectly stairlike because each terrace will have its peculiar angle of slope. The terraces are the topographic record of the succession of interrupted erosion cycles of which the unconformities in the stratigraphic sequence are the geologic record.

[1] Arthur Keith, "Some Stages of Appalachian Erosion," *Bulletin Geol. Soc. America*, Vol. VII (1896), pp. 519–24. "Geology of the Catoctin Belt," *Fourteenth Annual Report, U.S. Geol. Sur.*, Part II (1892–93), pp. 285–395.

[2] M. R. Campbell, "Geographic Development of Northern Pennsylvania and Southern New York," *Bulletin Geol. Soc. America*, Vol. XIV (1903), pp. 277–96.

[3] Joseph Barrell, "Rhythms and the Measurement of Geologic Time," *Bulletin Geol. Soc. America*, Vol. XXVIII (1917), pp. 745–904.

Nature is less obvious and more complex in her methods and evidences than such expectations would imply, but a detailed and careful study of approximately level tracts and benches seems to justify the following series of peneplains and terraces related to the major unconformities of the stratigraphic record.

Name	Altitude West–East	Sediments	Age	Preserved
Peneplains				
Kittatinny.....	1800–1600–1100	Patuxent.	Jurassic and Lower Cretaceous	Quartzite
Schooley.....	1300–1000–900	Patapsco-Arundel.	Lower Cretaceous	Granite
Honeybrook...	860–800–700	Raritan-Manasquan.	Upper Cretaceous	Granite
Harrisburg....	800–500	Aquia-St. Mary's.	Tertiary	Shale
Early Brandywine....	500–400–390	Early Brandywine.	Pliocene (Pleistocene)	Shale, etc.
Terraces				
Late Brandywine...	400–300–200	Late Brandywine.	Pleistocene	Mica gneisses
Sunderland....	300–180–100	Sunderland.	Pleistocene	Mica gneisses
Wicomico.....	90–45	Wicomico.	Pleistocene	Mica gneisses
Talbot.....	45–40–0	Talbot.	Pleistocene	Mica gneisses

The oldest peneplain, the highest inland from the sea and the lowest near the sea where it is preserved under sedimentary rocks, is the *Kittatinny*. This peneplain surface is so strikingly upheld,

FIG. 1.—Section across Godfrey Ridge and Kittatinny Range, at the Delaware Water Gap, Delaware Water Gap quadrangle, Pennsylvania–New Jersey.

although not preserved unmodified, by the indurated sandstone of Kittatinny Mountain (1,600 feet), its type locality (see Fig. 1), and in other resistant ridges of the Appalachian highlands that it was early recognized and an effort was made to fit it to the lower summits of Schooley Mountain and still lower surfaces in the

Piedmont province. In order to secure continuity between adjacent and discordant levels, it was necessary to assume abrupt and steep warping of the peneplain in some localities, and when accordance was secured it left unexplained the remarkable preservation throughout the Piedmont province of so ancient an erosion surface, and failed to explain why no records were preserved of the later continental movements and erosion cycles which are recorded in the sedimentary succession.

FIG. 2.—Kittatinny, Schooley, and Honeybrook peneplains in the Reading quadrangle. The summit of the ridge on the left at 1,140 feet represents the Kittatinny; the ridge in the middle at 1,000 feet, the Schooley; the ridge on the right at 700 feet, the Honeybrook peneplain. West Reading in middle distance, looking east.

The Kittatinny peneplain has been traced northeastward from the type locality to the base of the Catskill Mountains in New York, and westward and southward into Maryland and West Virginia. In the Blue Ridge province, surfaces which are probably remnants of the Kittatinny have altitudes of 1,800 feet in southern Pennsylvania (South Mountain), 1,300 on Blue Mountain to the northeast, and 1,200 feet in the quartzite ridge east of Reading (Penn Mountain, the dominating highland of the area, designated the Reading Prong of the New England upland). (See Figs. 2 and 3.)

Whether the Kittatinny peneplain is anywhere preserved in the Piedmont province of Pennsylvania is questionable. Reduced remnants of it may appear on Welsh Mountain (Honeybrook

quadrangle), a quartzite ridge, but, as is to be expected in a region so near the sea, erosion in subsequent cycles has probably modified the Kittatinny surface, notwithstanding the resistant character of the rock.

Near the "fall-line" where the lowest and oldest formations (Patuxent formation) of the coastal plain lie directly upon a peneplained surface of crystalline rocks, the floor which bears them may be that part of the Kittatinny peneplain which was submerged, was buried beneath sediments, and was thus preserved without modification while far inland the peneplain was still developing.

FIG. 3.—Schooley peneplain in the Reading quadrangle. The summit of Irish Mountain in the distance at 1,000 feet represents the Schooley peneplain, as seen from a point on the Early Brandywine peneplain, two miles east of Shoemakersville, looking south 45° east.

The Patuxent formation once overlapped the margin of the Piedmont province to a distance inland considerably greater than is now covered by it; but wherever it has been removed by erosion, the surface of the peneplain has been attacked so that the old surface cannot be found except perhaps in the immediate vicinity of the remnants of the formation. This surface lies at about 180 feet above sea-level, rising in Maryland to 280 feet. This first peneplain, carved on a dissected highland or possibly on uplifted peneplains, obliterated in this region all pre-existing erosion surfaces except those that were protected by a cover: an example of such a surface is to be found on Paleozoic rocks, where they are covered by Triassic formations (see Fig. 4). The later peneplains, carved on uplifted peneplains or terraces, never completely obliterated pre-existing erosion surfaces.

That the Kittatinny erosion cycle exceeded in duration any of the subsequent cycles must have been the case not alone because no subsequent cycle has been coextensive with it, but also because no subsequent cycle has succeeded in wearing down the most resistant rocks leveled by Kittatinny erosion and located well within the area of subsequent peneplanation.

The next oldest peneplain, the Schooley, with its type locality the granite summits of Schooley Mountain (1,300 feet), New Jersey, has been traced northward to the Mohawk Valley, westward to

FIG. 4.—Section of erosion surface on the Paleozoic, protected by a cover of Triassic rocks. Port Kennedy, Montgomery County, Pennsylvania.

Syracuse,[1] and southward to the Potomac.[2] In western New York it appears to coalesce with the Kittatinny, suggesting that in that region there was no uplift separating the two erosion periods.

At the Delaware Water Gap[3] the ridge between Godfrey Ridge and Kittatinny Range with summit areas at 1,000 feet may represent the Schooley peneplain, and Wind Gap between Blue Mountain and Kittatinny Mountain in Northampton County at the same elevation may have been a water gap during the early part of the Schooley erosion cycle. In the Blue Ridge province remnants are preserved in summit areas of 1,200 and 1,000 feet

[1] Memorandum by M. R. Campbell.

[2] Mem. by the writer.

[3] G. W. Stose, "Text of Delaware Water Gap Sheet," *U.S. Geol. Survey.*

altitudes. East and northeast of Reading there are many flat-topped granite and quartzite hills rising to a height of 1,000 feet, the Schooley level in that locality (see Figs. 5–10). On one of these, the Schooley remnant is separated from the adjacent Kittatinny

FIG. 5.—Schooley peneplain above the Honeybrook peneplain in the Boyertown quadrangle. The summit of Long Hill in the distance at 1,040 feet represents the Schooley peneplain, as seen from a point one-half mile southeast of Shanesville, looking south. The summit of the ridge in the foreground is a remnant of the Honeybrook peneplain.

FIG. 6.—Schooley peneplain in the Reading quadrangle. The higher parts of the past-maturely dissected upland one and one-half miles southeast of Fleetwood represent the Schooley peneplain at an altitude of 940–1,000 feet. Hill road, looking south on hills south of Princeton.

remnant by a steep slope (Fig. 9). In the central Piedmont province the Schooley peneplain descends to an altitude of 800 feet (Coatesville quadrangle). If the Schooley peneplain reappears near the "fall-line," it is found on the border of, and passing

beneath, the Patapsco formation, which rests upon eroded Patuxent, at an altitude of 100 feet, rising to 130 feet in Maryland. The next movement of uplift not only raised the Schooley peneplain

FIG. 7.—Schooley, Honeybrook, and Late Brandywine peneplains in the Boyertown quadrangle. High hills in the background are remnants of the Schooley peneplain, altitude 1,000 feet; hill in center in middle distance is at the level (660 feet) of the Honeybrook peneplain; and the foreground is on the Late Brandywine peneplain, altitude 420 feet. Looking west from Palm Station.

FIG. 8.—Schooley and Honeybrook peneplains in the Boyertown quadrangles. Hills in the background are remnants of the Schooley peneplain, altitude 1,000 feet; foreground on the Honeybrook peneplain, altitude 800 feet. Devil's Hump, looking south 30° west.

and remnants of the Kittatinny peneplain to a considerable height, but warped them.[1]

The next younger peneplain, the Honeybrook, appears in Godfrey Ridge, northwest of Kittatinny Mountain, at the Delaware

[1] Bailey Willis, *op. cit.*, pp. 189–90. C. W. Hayes, *op. cit.*, p. 330.

Water Gap, and on the hill summits southeast of Kittatinny Mountain at an altitude of 800 feet. This altitude is a very persistent one in the Appalachian Valley from this region to Susquehanna River. The Hamburg and Slatington quadrangles show the Honeybrook peneplain dominating the interstream areas. It retains an altitude of 800 feet in the Blue Ridge province and is well shown east of Reading, where Neversink Mountain, Guldin Hill, and the southeastern spur of Penn Mountain preserve its surface (see Fig. 9). The Honeybrook and the Schooley are here

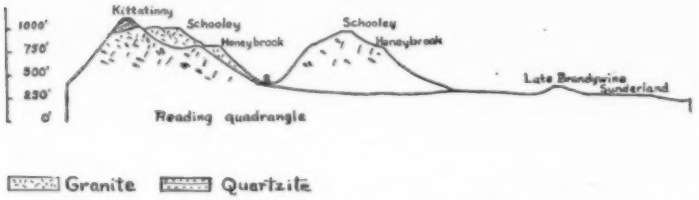

FIG. 9.—Section across Penn Mountain and Guldin Hill, showing remnants of the Kittatinny, Schooley, and Honeybrook peneplains, and of the Late Brandywine and Sunderland erosion surfaces. Reading Prong of the New England upland, Reading quadrangle, Pennsylvania.

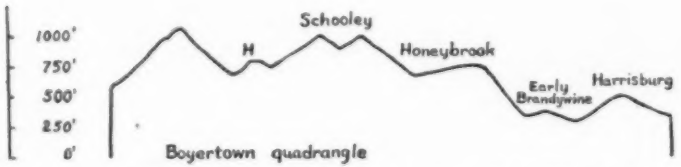

FIG. 10.—Section across Long Hill, Devil's Hump, and Gabel Hill, showing the Schooley, Honeybrook, and Harrisburg peneplains. Boyertown quadrangle, Pennsylvania.

found adjacent, are both cut in granite, and are separated by a steep slope (see also Figs. 11 and 12).

In the Piedmont province the Honeybrook descends to 700 feet. On the divide between Susquehanna and Schuylkill rivers the North and South Chester Valley Hills preserve this peneplain. The most extended remnant of it is found on the granite about Honeybrook, 16 miles south of Reading, and from this type locality

Science & Industry
Department

the peneplain is here named the Honeybrook.[1] It is not claimed that this plain has been traced throughout the Appalachian highlands division, but in the Piedmont province of Pennsylvania it

FIG. 11.—Honeybrook peneplain below the Schooley, Boyertown quadrangle. The upland in the distance represents the Schooley peneplain, altitude 1,000 feet, and that in the middle distance, altitude 800 feet, the Honeybrook peneplain, as seen from a point one-fourth mile southwest of Shanesville, looking north 15° west.

FIG. 12.—Water gap in a ridge whose summit is a remnant of the Honeybrook peneplain, Boyertown quadrangle. Upland in background, altitude 1,000 feet, represents the Schooley peneplain. Summit of ridge 800 feet and stream in the water gap, 440 feet. View from a point one-fourth mile southwest of Shanesville, looking north 45° west.

seems to represent a distinct erosion level between the Schooley and Harrisburg. The Honeybrook peneplain has been completely

[1] The Schooley peneplain was traced from Pennsylvania to the Potomac Valley in Maryland to surfaces (Green Ridges) which have been ascribed to the Weverton peneplain (*Maryland Geol. Survey*, Vol. VI [1906], pp. 87–88). Elsewhere in the central Piedmont of Pennsylvania the Weverton as defined corresponds to a lower peneplain than the Schooley. A new name has therefore been introduced for a redefined Weverton.

removed at the "fall-line." It passes under the Raritan (Upper Cretaceous) formation near the junction of the Coastal Plain and Piedmont.

FIG. 13.—Harrisburg peneplain in the Coatesville quadrangle. The dissected peneplain at an altitude of 600 feet, as seen one-third of a mile northwest of Humphreyville, looking southwest.

FIG. 14.—Harrisburg peneplain on Schuylkill River, in the Reading and Honeybrook quadrangles. The summit of the hill in the middle distance in which the river is cutting a steep bluff represents the Harrisburg peneplain, altitude 600–660 feet. Gibraltar Hill, 900 feet, a monadnock, on the left, and the Sunderland plain in the foreground, as seen from Lookout Point, Neversink Mountain, looking south.

The Harrisburg peneplain[1] has been restricted, with the approval of its sponsor, at its type locality northeast of Harrisburg to upland

[1] M. R. Campbell, *Bulletin Geol. Soc. America*, Vol. XIV (1903), pp. 277–96.

surfaces on the Ordovician (Martinsburg) shale which reach 600 feet, and to corresponding altitudes on Delaware and Potomac rivers (see Figs. 13 and 14). At this altitude it is widespread in

FIG. 15.—Honeybrook and Harrisburg peneplains in the Boyertown quadrangle. The Honeybrook peneplain corresponds with the surface of the upland on the left at an altitude of 800 feet and the Harrisburg with the upland in the distance on the right at an altitude of 600 feet, as seen from the northeast end of Long Hill, looking north 55° east.

FIG. 16.—Remnants of Early Brandywine and Harrisburg peneplains in the Harrisburg quadrangles. The surface of the upland represents the Early Brandywine peneplain upon which the hills, rising to an altitude of 740 feet and perhaps to the level of the Harrisburg peneplain, stand as monadnocks. The view is from a point on the Sunderland level one-half mile northwest of Maiden Creek, looking southwest.

the central Piedmont province and descends on the border of the upland to 500 feet (North and South Chester Valley Hills in the Schuylkill Valley). The Harrisburg does not appear in the "fall-line" zone, but probably descends below sea-level beneath the

Aquia Greensands (Tertiary), which lie far out on the Coastal Plain.

The Early Brandywine, the youngest and most widely preserved of the five peneplains, is found on Ordovician shale at the 500-foot level, northeast of Harrisburg. It contains at this altitude in the

FIG. 17.—Early Brandywine peneplain in the Boyertown quadrangle. The peneplain corresponding with the surface of the upland in the distance at an altitude of 560 feet is seen from a point one-half mile west of Eschbach, looking south 45° east.

FIG. 18.—Early Brandywine peneplain in the Reading quadrangle. The peneplain at an altitude of 500 feet is represented by the surface of the upland in the distance, as seen from a point on the Sunderland level one-half mile northwest of Maiden Creek, looking south 65° west toward Leesport.

valley of the Delaware at the Water Gap and in the Schuylkill and Potomac valleys (Antietam quadrangle). It ranges from 400 to 450 feet in the Piedmont upland of Pennsylvania where, as is to be expected, because it is the most recently formed peneplain, it is the most pronounced upland level (see Figs. 15–18).

West Chester is located upon this peneplain surface, which is the dominant altitude throughout the West Chester quadrangle (see Figs. 19 and 20). At 400 feet it carries Early Brandywine gravel and sand, 10 miles west of the "fall-line" zone. It has been named the Early Brandywine from the formation which is found at this altitude and on the seaward continuation of the slope. This peneplain is correlated with the so-called Lafayette[1] terrace recognized in Maryland[2] but a more widespread extension is claimed for the Early Brandywine peneplain.

The Early Brandywine peneplain is everywhere submaturely dissected. The summits of the interstream areas preserve the peneplain, gentle slopes from these summit remnants lead to the gorges (Pleistocene) of the main streams and of the larger tributaries or form the U-shaped valleys of headwater streams. These slopes have an elevation inland from 300 to 400 feet and in the "fall-line" zone from 200 to 300 feet (see Figs. 21–25).

Following the deposition of the Early Brandywine formation and before the deposition of the Sunderland formation, the whole continental shelf was brought above the sea and master-streams of the Atlantic plain were extended to the edge of the continental shelf. To this period, which may have been well within Pleistocene time, is attributed the formation of the Late Brandywine benches and slopes. Few formations can be correlated with it, as the

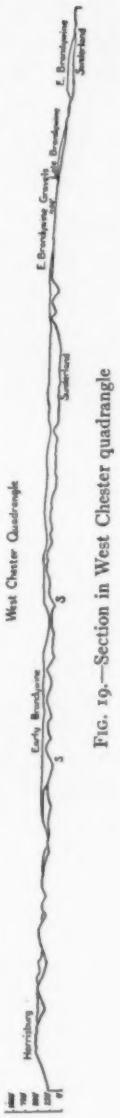

FIG. 19.—Section in West Chester quadrangle

[1] Owing to the change of the name Lafayette to Brandywine, the more recent name has been given to the peneplain. The name Brandywine is taken from a village of that name in Prince George County, Md., where the formation is reported to be characteristically developed. The position and level of the gravel of this type locality at 233 feet seem to indicate that it is the low-level Brandywine or Late Brandywine gravel as it is provisionally named in this paper.

[2] *Maryland Geol. Survey*, Vol. VI (1906), pp. 59–60.

marine sedimentation of the period took place, mainly at least, beyond the continental shelf. Gravel, which has been included in the "Brandywine" (Early and Late Brandywine), but which lies at all places at a lower level than the Early Brandywine gravel, is thought to be a terrestrial deposit of Pleistocene streams. Such gravel is found on the Chester quadrangle at an altitude of 300 feet and on Elk Neck, Elkton quadrangle, between 200 and 300 feet.

The records of this period of erosion are the dissection of the Early Brandywine peneplain, producing the stream terraces and

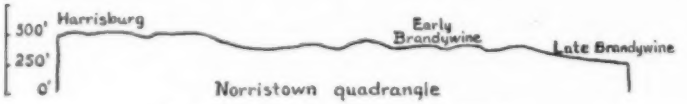

FIG. 20.—Section in Norristown quadrangle

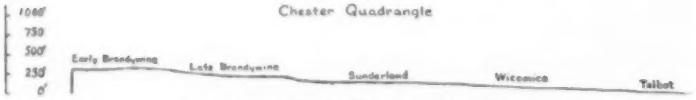

FIG. 21.—Section in Chester quadrangle

the slopes which separate the Early Brandywine peneplain and the Sunderland terrace, and the submerged valleys on the continental shelf. Late Brandywine slopes are well defined on the Chester quadrangle, and furnish a commanding site for the buildings of Swarthmore College.

The Sunderland, Wicomico, and Talbot terraces have been recognized and defined in Maryland.[1] In Pennsylvania a scarp separates the Late Brandywine and the Sunderland. This scarp, which the central building of Swarthmore College fronts, represents either the old estuarine shore cliff or the escarpment of the wide meander belt of Delaware River.

Erosion truncated the Late Brandywine slopes and dissected them and the Early Brandywine peneplain along drainage ways. What has been called the Somerville peneplain seems to the writer

[1] *Maryland Geol. Survey*, Vol. VI (1906), pp. 61–67.

to be such an inland extension of erosion during the Sunderland cycle.

In general the Sunderland extends from the 100 to the 180 contour lines: the Wicomico from the 80 to the 90 contour lines, and the Talbot, where it does not coalesce with the Wicomico, from the 40-foot contour to sea-level. These three terraces are conspicuously developed in eastern Pennsylvania parallel to Delaware River. In Maryland the Wicomico and Talbot terraces are in some places obliterated and the Sunderland reaches the edge of the beach with a cliff 100 feet high, but this is not the case in Pennsylvania where the terraces are not seacoast features.

The Wicomico terrace wraps about the Sunderland as the Sunderland does about the Late Brandywine, with usually a well-marked break between the two, except in the gorges of the tributary streams. The Talbot terrace borders the Wicomico, which it penetrates along drainage ways, and in some places parallel to Delaware River coalesces with the Wicomico.

It has not proved practicable to show by graphic means the distribution of the remnants of the peneplains and terraces in the Piedmont province of Pennsylvania. It may be stated that in general the oldest peneplain is farthest inland and the youngest nearest the shore, with those of intermediate age ranging between. If this region had been one of uniform resistance to weathering, there would have been a perfect operation of this law of areal

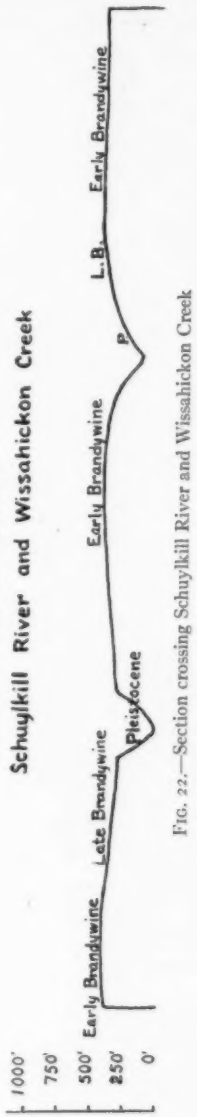

FIG. 22.—Section crossing Schuylkill River and Wissahickon Creek

distribution: the areal succession of peneplains from interior to coast would exactly accord with the chronological succession. The region is, however, one of varied structural and lithologic resistance to weathering and the peneplains are not therefore so simply spaced; younger peneplains on relatively weak rocks are found inland at higher altitudes than the marginal remnants of older peneplains. This fact would be still more apparent if the extreme margins of the older peneplains, now buried beneath sedimentary formations, were shown.

The question of the origin of these peneplains, that is, of the nature of the dominant erosive agent, is open to debate. The

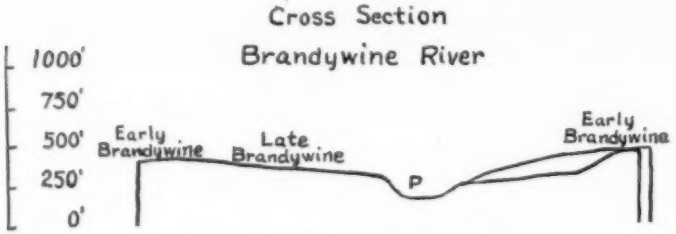

FIG. 23.—Section crossing Brandywine River

three youngest terraces, in Maryland presumably of marine origin, are in this region of fluvial-estuarine or of fluvial origin; that is, they were developed on the borders of the Delaware estuary or on a shrinking meander belt of Delaware River.

That the Late Brandywine is of subaerial origin is concluded from the evidence of the valleys, now submerged, which extend across the continental shelf and which it is believed were excavated in Late Brandywine time.

That the five peneplains are in part of marine and in part of subaerial origin seems a warranted conclusion. Each peneplain was partly submerged and carries marine sediments, but there does not seem to be sufficient proof that any one peneplain was completely submerged. They parallel the coast line as would be the case were they of marine origin, but this may also be true of subaerial peneplains, and the great inland extension of the Kittatinny

Science & Industry
Department

and Schooley peneplains with an indefinite thin margin is indicative of subaerial erosion. The contact of the Honeybrook and Schooley peneplains, on the Reading quadrangle, on the other hand, suggests

FIG. 24.—Late Brandywine peneplain in the Reading quadrangle. The peneplain at an altitude of 400 feet, as seen from the hillside south of Oley Furnace, looking south toward Friedensburg.

FIG. 25.—Honeybrook and Late Brandywine peneplains in the Reading and Boyertown quadrangles. The surface of the upland in the distance at an altitude of 800 feet represents the Honeybrook peneplain, and the level land in the middle distance at altitudes ranging from 400 to 440 feet, the Late Brandywine peneplain, as seen from a point one-fourth miles southwest of Oley Furnace, looking south 45° east toward Shenkel Hill.

a sea cliff. In the case of the Harrisburg and Early Brandywine peneplains definite proof of subaerial or marine origin has not been found.

THE HORIZONTAL MOVEMENT OF GEANTICLINES AND THE FRACTURES NEAR THEIR SURFACE

H. A. BROUWER
Delft, Holland

Most islands of the arcs which lie to the east and the southeast of the Asiatic continent show proof of an uplift of the land relatively to the sea-level, which is amply demonstrated in tropical regions by the presence of upheaved fringing reefs. In the East Indian Archipelago there exists a striking difference between the western and the eastern parts as regards the rising islands and the submarine topography. If the sea-level were to be lowered 200 m., Sumatra, Java, and Borneo would form one mass of land with the peninsula of Cambodia and Siam, just as Australia would form a single mass with the Aru Islands through the vast tract now occupied by the shallow Arafura Sea and the Bay of Carpentaria to New Guinea and the islands Misool, Waigeu, Batanta, and Salawati to the west of New Guinea.

Between these two near-land-masses lies an area in which deep sea basins alternate with upheaved islands. From a geological point of view Verbeek[1] first drew attention to this remarkable fact, of which a more satisfactory discussion has been made possible because of the new deep-sea chart of the Siboga Expedition.[2] In Verbeek's opinion the elevation of the islands surrounding the Banda Sea is the result of folding at greater depth. The active forces first began compressing near the surface, and as the geosynclines were formed they became active at greater depths. Later Molengraaff[3] expressed similar ideas, and for the southeastern por-

[1] R. D. M. Verbeek, "Rapport sur les Moluques," édition française du *Jaarb. v. h. Mijnwezen in Ned. O. Indië*, Vol. XXXVII (1908), pp. 833, 834.

[2] G. A. F. Tydeman, "Hydrographic Results of the Siboga Expedition," Chart 1, in M. Weber, *Siboga-Expeditie*, Part III, Leyden, 1903.

[3] G. A. F. Molengraaff, "Folded Mountain Chains, Overthrust Sheets and Block-Faulted Mountains in the East Indian Archipelago," *Compte rendu du XII^e congrès géologique international*, Toronto, 1913, p. 699.

tion of the Malay Archipelago he distinguished two types of mountain-building: (1) the overthrust type of Miocene age, culminating in overthrusts of great magnitude, which was the expression of a very powerful, but not deep-seated compression, and (2) the block-faulted type of Plio-Pleistocene age, consisting of ranges of elevated islands alternating with deep sea basins, these being the expression of a deeper-seated, but perhaps less energetic compression.

It is only the vertical movements of the rows of islands that have been considered by these authors. In some recent publications[1] I have pointed out that:

1. The youngest crustal movements in this region are a younger phase in the same process as the older and an exact continuation of the mid-Tertiary crustal movements. Of the mid-Tertiary phase we know only the folds and overthrusts which represent action at greater depth; of the youngest phase only the fractured and faulted crust which represents action near the surface; but the two phenomena are mutually complementary and the rows of uplifted islands indicate the spots where the folding process continues at the greater depths with the same tendency to form overthrusts.

2. From the outline of the rows of islands we may conclude that they have a large movement in a *horizontal* as well as in a vertical direction.

The horizontal movements of the curving rows of islands are expressed by several of their characters.

1. The striking fact that the Tenimber Islands and the Kei Islands have an outlying position in the row and both are situated opposite a depression in the Sahul bank which constitutes the Australian continental shelf. Opposite these depressions the geanticline met with less resistance.

[1] H. A. Brouwer, "On the Crustal Movements in the Region of the Curving Rows of Islands in the Eastern Part of the East Indian Archipelago," *Proceed. Kon. Akad. v. Wetensch. Amsterdam*, Vol. XXII, pp. 772–82; "On Reef Caps," *ibid.*, Vol. XXI, pp. 816–26; "Fractures and Faults near the Surface of Moving Geanticlines," *ibid.*, Vol. XXIII, pp. 570–76; "Über Gebirgsbildung und Vulkanismus in den Molukken," *Geol. Rundschau*, 1917, p. 197; "Über die horizontale Bewegung der Inselreihen in den Molukken," *Nachr. d. Gesellsch. der Wiss. zu Göttingen*, 1920.

2. The coincidence of asymmetrical reef caps with marked outward bends of the row of islands, instances of which are found in the island Rotti to the southwest of Timor and in the island Jamdena of the Tenimber group.

3. The faults and fractures near the surface demonstrate differences in rate of horizontal movement between adjacent parts of the moving geanticlines.

In the following pages the above-described faults and fractures will be dealt with in connection with the vertical and horizontal movements of the geanticlines near the surface of which they occur. Because the geanticlines have risen from the sea and were in consequence exposed to eroding influences during a much shorter time than those of the continental mountain ranges, the outer form is not in the main controlled by erosion, but by the crustal movements themselves, and the latest phase of mountain-building manifests itself clearly in the shape of the geanticlines near the surface.

CRUSTAL MOVEMENTS AND MORPHOLOGICAL STRUCTURE

When crustal movements take place they generally cause the strata to break near the surface and to fold at greater depths. An extension of the geanticlinal axis is here obtained through gaping fractures, or by movements parallel to fault planes which must be inclined to the geanticlinal axis. Shortening of the geanticline is possible by faulting along fault planes which are not perpendicular to the geanticlinal axis. Similar relations prevail for a lengthening or a shortening of a section of the geanticlinal surface with a plane perpendicular to the geanticlinal axis.

In addition to the control by the direction and the rate of the movement, the position of the fault planes is determined by a great many other factors, e.g., by stratification and by the composition and distribution of the rocks near the surface. Leaving out of consideration those local areas within which the anticlinal axis shows an important pitch, the morphological aspect of the surface will be controlled chiefly by the more or less horizontal transverse faults, the gaping transverse fractures, the more or less longitudinal faults, and the gaping longitudinal fractures.

We are here considering those regions only of the geanticlinal surface where the faults, through their more or less equal position

and their more or less equal direction of movement, bring about considerable alterations in the broad outlines of the morphological structure. Zones of constant lithological characters will generally be separated near the surface by planes which are parallel to the geanticlinal axis. If these planes are more or less vertical, this will chiefly influence the distribution of the vertical longitudinal fractures and the longitudinal faults. If these planes are principally more or less horizontal, this will chiefly influence the distribution of the faults along horizontal planes, but they will be of little importance for the major morphological structure and will here be left out of consideration. Whether these planes are nearly vertical or nearly horizontal, the lithological character is of little importance for the distribution of the transverse faults and fractures which strongly influence the morphology at the surface of the geanticline. Thus we find that the outline at the surface is mainly controlled by the direction and the rate of the crustal movements in so far as the transverse fractures are concerned.

OLDER FOLDS CUT OFF BY THE PRESENT COAST LINE

The surface and the deeper parts of moving geanticlines will generally not move in the same direction and at the same rate, because:

1. The intensity and likewise the direction of the forces which cause the movement near the surface will generally be different from those which obtain at greater depth.

2. The transmission of directed forces will decrease from the surface to the zones of higher plasticity at greater depth.

If the forces which cause the movement are deep-seated, and the crust near the surface does not respond to the direct influence of the compressional or tensional stress, the displacements near the surface will be the result of the movement at greater depth. In forming a judgment on the genesis of fractures and folds this should be borne in mind.

A result of the difference between the movements at greater depth and those near the surface is that, if at greater depth the movement has a horizontal component, those points which were originally on the same vertical line will in a later stage of evolution of the geanticline form an irregular curve, the form of which will

depend upon the direction and the rates of movement at different depths. If a geanticline is elevated above the sea, the deeper-seated parts will gradually be uncovered by erosion and the surface of the geanticline will in time consist of rocks which were in the zone of flow during an earlier stage of the mountain-building process. As they are approaching the earth's surface, the rate and the direction of the motion may differ more and more from those at greater depths on the same vertical line.

That older folds terminate abruptly against the present coast lines is a phenomenon which is well known from Japan and from several islands of the East Indian Archipelago (Fig. 1). Particularly on Ceram this fact is very strikingly exemplified. In the

FIG. 1.—Older folds terminating abruptly against the present coast lines of the island of Ceram. (East Indian Archipelago.) Scale 1:3,000,000. ------ Approximate Tertiary strike.

greater part of the island the strike of the Tertiary mountain range is NW.–S.E., whereas the present coast line has for the middle part an east–west direction, so that the ridges of the high mountains terminate abruptly near Taluti Bay on the south coast and near Savai Bay on the north coast.

Similar facts have been explained by von Richthofen[1] as a result of tensional stress on a large scale, and he believed that the mountain arcs of eastern Asia, although bearing a great resemblance to the Alps and the Himalayas, have been formed by tensional, and not by compressional stress. Various authors have pointed out that this conception is not exact, and particularly because the fractures resulting from tensional stress are generally straight, whereas the ranges which lie to the eastward of the

[1] F. von Richthofen, "Geomorphologische Studien aus Ost-Asien, IV," *Sitzungsber. der Berlin. Akad. der Wiss.*, XL (1913).

Asiatic continent are arcs which present their convex sides to the oceanic areas. The tension hypothesis of Von Richthofen has been applied by some authors to the East Indian Archipelago, but the numerous fractures which without doubt exist near the surface can be explained in a simpler manner by the action of compressional stress.

It is not necessary to distinguish two periods of folding with different directions of the compressive forces, if we have regard for the fact that the older folds are cut off by the present coast lines. If the strike of the older folds is independent of the outlines of the present rows of islands, this may be in part a result of a change in the direction of the compressive forces; but it can be entirely a result of the fact that the folds which now appear at the earth's surface have been formed in a much earlier stage of evolution of the geanticline, and that during their elevation the horizontal component of the rate of movement was different for neighboring parts of the geanticline, while the transmission of the directed forces has increased and the intensity and the direction of the forces has changed, whereas at greater depths the plastic deformation has continued.

GROUPS OF SMALL ISLANDS WITH HIGH REEFS

In many rows of islands the breadth of each island is in direct proportion to the amount of elevation. In the Timor-Ceram range the long and broad island of Timor shows elevated reefs at the altitude of 1,300 m. in its central part, whereas in the short and much narrower island of Rotti elevated reefs are known at an altitude of but 470 m. This will generally be true wherever the vertical motion prevails. The increase in breadth results from the fact that the vertical component of the rate of movement has generally been in the same direction near the coast as it has near the axis of the geanticline. If the distance of the geanticlinal axis from the coast line be considerable, the vertical component of the movement need not be the same for longitudinal and for transverse coasts. The length of the island may still increase though the breadth decreases, or both may decrease and the island get shorter and narrower, while the top is still moving upward. However, if the geanticline shows

a normal evolution, high reefs will always be found on large islands.

If this is not the case, and if adjacent small islands show elevated reefs at high altitudes, this points to the existence of fractures. This case is illustrated by the islands of the Babber group (Fig. 2). Some fine specimens of terraced islands are found in this group. In Babber the uppermost elevated reefs are found at an altitude of 650 m.;[1] the small island of Dai with a steep coast has fifteen terraces, the highest at 620 m. above sea-level; the small island of Dawera has probably sixteen terraces; and Daweloor has fourteen entirely covered with reefs. On Dawera the highest point is at an altitude of 328 m., and on Daweloor of 280 m. On Wetan, which also consists entirely of upheaved reefs, there are six or seven terraces in the southern part with a maximum altitude of 320 m. Wetan is separated from Babber by a narrow and deep strait without reefs.[2] Kisser, a small island of the Sermata group shows the same characteristics, having a fine terraced appearance with the highest reefs at an altitude of 147 m., though in the neighborhood of its coasts the sea bottom falls off rapidly to great depths.

FIG. 2.—The islands of the Babber group. (Southeastern Malay Archipelago.) Scale 1:3,000,000. 320, etc., altitude of the uppermost elevated reefs in meters. 200, 500, 1,000, submarine contours in meters.

THE EVOLUTION OF PARALLEL ROWS OF ISLANDS AND LONGITUDINAL FRACTURES STUDIED IN THE PROFILE

If we consider the evolution of geanticlines in a direction parallel to the geanticlinal axis, we find long and high islands where they are highest, and small and low islands at the depressions of the

[1] F. A. H. Weckherlin de Marez Oyens, "De Geologie van het Eiland Babber," *Handel. v. h. XIVe Nat. en Geneesk. Congres* 1913, pp. 463–68.

[2] R. D. M. Verbeek, *op. cit.*, p. 458.

axis. In the present-day stage of mountain-building this fact is illustrated by the Timor-Ceram row of islands, where a well-marked culmination occurs in the central part of Timor and well-marked depressions are found to the east and to the west of it. Secondary culminations and depressions are also found.

Sometimes two more or less parallel ranges of islands have the same direction as the geanticlinal axis. An example in the East Indian Archipelago is supplied by the islands of the Tenimber group, where the row which includes the main island Jamdena is

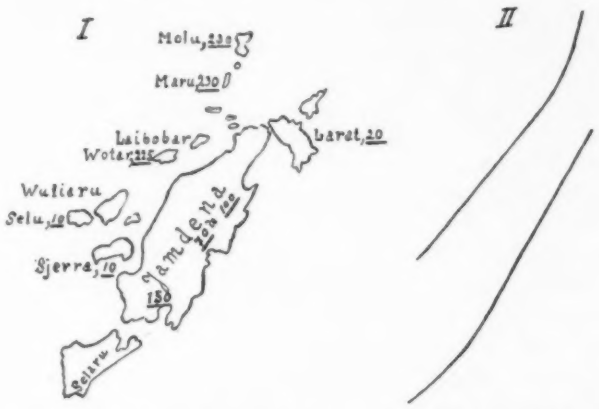

FIG. 3.—I, The islands of the Tenimber group. (Southeastern Malay Archipelago.) Scale 1:3,000,000. 225, etc., altitude of the uppermost elevated reefs in meters. II, The axes of the two secondary geanticlines (schematic representation).

accompanied by another row including the islands Selu, Wuliaru, Wotar, Laibobar, Maru, and Molu. The latter row differs from that of Jamdena in that it consists of smaller islands, although the elevated reefs are known at higher altitudes. On Wotar they are found at an altitude of 225 m., whereas on the main island Jamdena of the southern row the greatest height is at most 150 m. The reef cap, which covers Jamdena nearly continuously, is asymmetric, rising gradually from the northwestern coast in the direction of the main watershed of the island and thence descending rapidly toward the southeastern coast. I have explored portions of the coast of

the gently sloping northwestern part of this asymmetrical geanticline and found drowned river valleys which were observed far inland from the coast. Thus the upheaved island Jamdena is separated from the row of upheaved islands to the northwest by a zone which is covered by the sea, and in which during the youngest evolution of the geanticline positive movements have prevailed.

These facts can be explained in much the same way as has been done by Escher[1] for the group of islands southeast of Celebes which are known as the Tukang Besi Islands and which consist of four rows. Two of these rows consist of islands with elevated reefs which mark the anticlinal axes, whereas the two remaining show barrier reefs and atolls which mark the synclinal axes (Fig. 3).

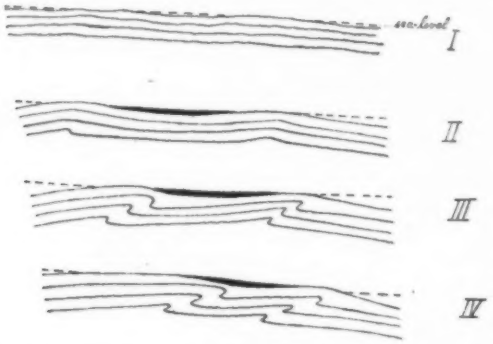

FIG. 4. One of the possible evolutions of two parallel rows of islands, of which different phases are represented in the southeastern Malay Archipelago (schematic representation). IV, Stage with elevated central basin.

We suppose that the geanticline at the Tenimber Islands is developing as two secondary geanticlines with an intermediate secondary geosyncline. The greater breadth of the islands in the southeastern secondary geanticline (although the reefs are not elevated to higher altitudes) may be the result of the prevalence of horizontal movements which caused the development of the asymmetrical reef cap (Fig. 4).

[1] B. G. Escher, "Atollen in den Nederlandsch Oost-Indischen Archipel: De Riffen in de Groep der Toekang Besi Eilanden," *Meded. Encyclop Bureau*, Afl. XXII (1920).

The further evolution of the geanticline can take place in different ways. If we suppose that in the next stage the plastic deformation of the northwestern secondary geanticline at greater depth causes chiefly a movement in a horizontal direction, the region of strongest upheaval will be displaced to the southeast. We may suppose that the rows of islands move in the direction of Australia, which for our considerations is the same as if Australia moved in the direction of the row of islands. Hobbs[1] has pointed out that mechanical difficulties disappear if the principal active forces involved in the folding of the Alps are considered as directed from the northwest toward the southeast. So far as our general conclusions are concerned, we may consider these movements as relative and not as absolute. The upper parts of the secondary geanticline do not move at the same rate and the higher parts of the folds were originally above the downward-moving secondary geosyncline. In a later stage of evolution these may be above the rising northwestern secondary geanticline and will be elevated above the sea.

Though differing in details, the geanticline of Timor may represent a later stage of geanticline evolution than the Tenimber Islands. In Pliocene time the geanticline near Timor was subjected to prolonged denudation and almost entirely disappeared below the sea. The crustal movements resulted in the development of two geanticlines and an intermediate, in part subdivided, geosyncline (cf. Molengraaff, *op. cit.*, p. 694), which became throughout fairly well filled by an accumulation of late Tertiary sediments deposited during a period of slow subsidence. Flexures and faults of considerable horizontal extent occur in the limbs of the geosyncline, which have caused the Pliocene strata within the basin to become bent abruptly upward near the edges. These longitudinal flexures and faults, which are essentially the same phenomenon, are the surface expression of an earlier, more plastic deformation at greater depth. Reefs and other littoral deposits spread over a great area, and after a certain period of evolution a great portion of Timor must have been covered by a sea full of

[1] W. H. Hobbs, "Mechanics of Formation of Arcuate Mountains," *Journal of Geology*, Vol. XXII (1914), p. 85.

coral islands and reefs, from which the islands emerged which are now the higher mountain groups of the present much enlarged island.

A similar stage of evolution is now to be observed in the same range of islands more to the east. The islands of the Sermata group clearly illustrate the movements of reefs in the period of development of the geanticline in which only its highest parts emerge from the sea as a group of smaller islands. The island of Luang has an altitude of 260 m. and, according to my observations, is built up entirely of Permian rocks. Together with two small islets at its southeastern extremity, it is fringed by a very broad reef, extending far to the east in the direction of Sermata and far to the west as well. Green islets far from the north coast, and barren, dry portions far from the south coast, mark the limits in northern and southern direction; beyond them the sea floor declines rapidly. Luang as well as the two small islets close to it rise up steeply from this broad reef, and no trace of elevated reefs was detected; the islands impress us as having originally formed one continuous whole and as having been separated by a positive movement, which may also account for the formation of the broad encircling reef.

In its eastern part the island of Moa consists of a low, very broad plateau of coral limestone, which rises scarcely more than 10–20 m. above the sea. From this plateau rises the steep Kerbau Mountain to an altitude of 400 m. Elevated reefs are lacking on the slopes of this mountain, and if the eastern part of Moa were a little lower, this region would present an aspect similar to that of Luang. The Island of Lakor, between Luang and Moa, consists of a low coral plateau, and Meaty Miarang forms the southern part of a large atolliform reef on the northern part of which lie the two low Ukenaö Islands. To the east of Luang and to the west of the eastern part of Moa the reefs are elevated to much greater altitudes and the group of the Sermata Islands shows a well-marked depression of the geanticlinal axis of the Timor-Ceram row. This part is much disturbed by transverse fractures and no sufficient data are available for judging whether the submersion observed on some islands is the consequence of the pitch of the geanticlinal axis only, or whether this region has passed, or will in the future

pass, through a stage with a secondary geosyncline between two secondary geanticlines.

After the Plio-Pleistocene reefs had been formed, a general elevation of the island of Timor took place. The elevation of the land has been somewhat greater at the edges of the secondary geosyncline than in the geosyncline itself, but the general movement resulted in the formation of a large anticline with the highest elevated reefs in the central part of the present island. In this latter stage of evolution the horizontal movements near the surface may have had a much smaller rate of movement than those at greater depth, while the central basin was gradually upheaved above the sea. The horizontal movement at greater depth may have prevailed in one of the secondary geanticlines only, but this is not a necessary condition. In our Figure 4 one of the possible modes of upheaval is represented.

DIFFERENT TYPES OF GEANTICLINAL MOVEMENT

The movement of a geanticline can be broadly described in the first place, in terms of the movements of the projections of the geanticlinal axis on the horizontal plane and on a vertical plane approximately parallel to the part of the geanticlinal axis under consideration. It is next of importance to take note of the movement of the section of the surface of the geanticline with a vertical plane at right angles to the geanticlinal axis. At the beginning of the movement we consider the geanticlinal axis to be a straight line; in a later stage this line will not be the geanticlinal axis, but for an approximate judgment this method is sufficient. The projections would undergo no changes in form if the geanticlinal axis was displaced parallel to itself. In general the vertical as well as the horizontal projection will develop a curved form. Some general types are given in Figure 5.

In Diagram I of Figure 5 the differences of plasticity and rate of movement between the surface and the deep-seated parts will have an influence on the development of longitudinal fractures only. The deformation of the sections perpendicular to the geanticlinal axis will be influenced by the place, the speed, and the duration of these fracture movements.

In Diagram II of the same figure the same considerations apply. The bending of a_2^1 will be much less than that in the figure, and the distinct traces of transverse fracture movements on the islands will disappear rapidly through erosion, although they may be perceptible near the transverse coasts.

In Diagram III of the figure more or less longitudinal fractures may develop, which in connection with the deformation of the

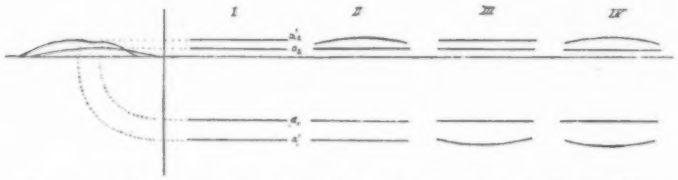

FIG. 5.—I, Displacement of the geanticlinal axis parallel to itself. II, III, and IV, Displacements in which the vertical or the horizontal projection, or both, have obtained a curved form.

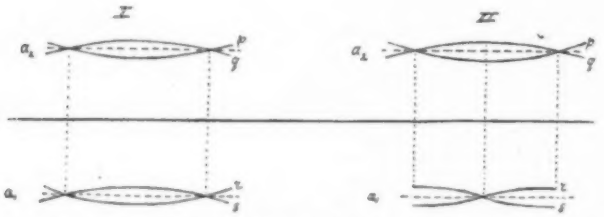

FIG. 6.—Deformations of the horizontal and vertical projections of the geanticlinal axis neglecting any displacements parallel to themselves.

sections perpendicular to the geanticlinal axis will be more or less important. Transverse fractures may be observable especially at the straits between the different islands of a row. Diagram IV is a combination of Diagrams II and III.

If in Diagram II, a_2^1 has one or more bending-points, which is equivalent to the development of transverse folds normal to the geanticlinal axis, then the place, rate, and duration of the transverse fracture movements near the surface may be strongly influenced by these folds. The same considerations are applicable to IIIa_1^1, and to IVa_2^1 or IVa_1^1, or to both of them.

If we consider Diagram IV, the more general type of deformation, supposing that the horizontal and the vertical projections of the geanticlinal axis have an equal number of bending-points, then two different types can be distinguished according as the bending-points of the horizontal and vertical projections alternate or do not (Fig. 6).

In this figure the combinations *p-r*, *q-s*, *q-r*, and *p-s* are different curves in space to which the originally rectilinear geanticlinal axis *a* has been distorted. The displacement of the geanticlinal axis parallel to itself and the distortion of the sections perpendicular to the geanticlinal axis are left out of consideration. The bending of *p* and *q* is much less than that which is shown in the figures. It would be more important if a strong compression had been acting in the direction of the geanticlinal axis from which would result a deformation to transverse folds normal to the geanticlinal axis. In this connection it is necessary to consider the geanticline over sufficiently long distances to obtain a judgment concerning the deformation of the vertical projection of the geanticlinal axis.

APPLICATION TO THE TRANSVERSE FRACTURES OF THE TIMOR-CERAM ROW OF ISLANDS

If considered over large distances it might seem that the geanticline, Sumba-Rotti-Timor-Sermata Islands, represents approximately Type I. The uppermost elevated reefs are found in Central Timor at an altitude of 1,300 m.; in West Timor, southeast of Kupang, they are at a height of 500 m., on Rotti at 470 m., and on Savu at 300 m. In East Timor the altitude is estimated at 600 m., on the islands farther to the east such reefs are known at altitudes of 140 m. on Letti and of 20 m. on Lakor, while on Luang no elevated reefs are found (cf. also Fig. 7). Thus the part, Sumba-Savu-Rotti-West Timor of the geanticline, would represent approximately I *p-r*, and the part, Central and East Timor–islands farther to the east, would represent I *q-s*.

If considered in detail the deformation is much more complicated. The deformation of the vertical projection is very slight and in many cases it is not exactly known. If the motion of the geanticlinal axis parallel to itself be neglected, this projection

nearly coincides with a, and the distinction between I a_2-r, I a_2-s and II a_2-r, II a_2-s disappears. Between Rotti and West Timor (Fig. 7) II p-r may be represented, but the deformation of the horizontal projection is the only important one.

The strait between Timor and Rotti coincides with a bending-point of the horizontal projection of the geanticlinal axis. In seeking an explanation for the existence of this strait, we might suggest the pitch of the geanticlinal axis on both sides of the strait, while at the place of the strait the axis could disappear below sea-level. But if considered in detail, this explanation alone is not applicable. On Rotti we find between the main island and the peninsula of Landu a narrow strait which only recently has been

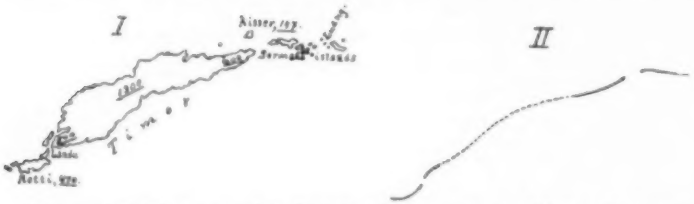

FIG. 7.—I, Rotti, Timor, and the Sermata Islands. 470, etc., altitude of the uppermost reefs in meters. Straits and transverse dislocations are near the bending-points of II. II, Geanticlinal axis with bending-points between Timor and Rotti and between Timor and the Sermata Islands.

filled up by a mud bank still inundated at spring tide. At both sides of the narrow strait high walls of elevated coral limestone occur, and during an exploration of the island I found a small isolated rock composed of coral limestone which emerges from the mud in the middle of the strait. These facts point to the existence of transverse gaping fractures formed by a movement with a component normal to the fracture plane. We have already mentioned similar facts in connection with the groups of small islands having high reefs.

Another example of the same sort is found to the east of Timor (Fig. 7). Considering the large bendings only, a bending-point is located between East Timor and the Babber group; but if considered in detail bendings of smaller amount may also be observed. We note a bending of the geanticlinal axis between East Timor and

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Letti of the Sermata group, and in the neighborhood of the bending-point we observe the northern, non-harmonic position of the small island Kisser which is covered by elevated reefs and surrounded by deep seas. There is here again the evidence that bending of the geanticline at greater depth is accompanied by transverse fractures near the surface. The fractures which occur farther to the east and their connection with the sharp bending in the 200 m. contour line of the Sahul shelf has already been discussed in earlier papers.[1]

Still another example is found between Ceram and Buru (Fig. 8). A very striking irregularity in this portion of the geanticline is the narrow Manipa Strait, nearly 5,000 m. deep between Ceram and Buru, here also near the bending-point of the horizontal projection of the geanticlinal axis. If this bending-point is not so clearly visible in the present topography, for the reason that the fracture movements are very strong, it may be inferred from the strikė of the Tertiary mountain range. In West Buru and in the greater part of Ceram this strike is about NW.–SE., whereas in West Ceram and in the islands between Ceram and Buru it is E. NE., and NE. strikes also have been observed (cf. Fig. 1).[2] Thus the Tertiary mountain range displays a considerable bending from Ceram to Buru. As we have pointed out, the strike of the folds and the overthrusts of the Tertiary phase of crustal movement, and

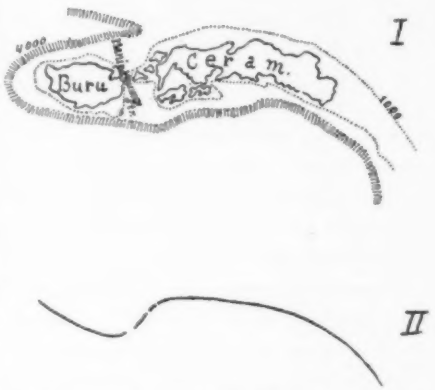

FIG. 8.—I, The deep Manipa Strait (+4800 m.) between Ceram and Buru. 1000, 4000, submarine contours. II, Geanticlinal axis with strong transverse dislocations near the bending-point.

[1] H. A. Brouwer, *loc. cit.*

[2] L. Rutten and W. Hotz, "De geologische Expeditie naar Ceram," *Tydschr. Kon. Ned. Aardr. Gen.*, Vol. XXXVI (1919), 9e Verslag.

the fractured and faulted crust near the surface of the youngest phase of the deformation are the result of different stages of the same process. As has been stated above, p and q will nearly coincide with a_2, and the bending of p and q is much less than is represented in the figures. In the case of the Strait of Manipa a compression may even have been acting in the direction of the geanticlinal axis so that the origin of the strait may in part be due to transverse folding. But no sufficient data are as yet available for an exact judgment on the problem of deformation in space.

We have seen that in the large bendings of the geanticlinal axis a distinction between Types I and II can be made, though if considered for bending at relatively small distances, these two types are very similar for the reason that p and q nearly coincide with a_2. In the Timor-Ceram row the following rule seems to be approximately applicable:

Considerable transverse fractures near the surface of the moving geanticline coincide with bending-points of the horizontal projection of the geanticlinal axis.

In most cases it is clearly observable that the fractures near the surface have been formed by a movement having an important component normal to the fracture plane, and that the fractures near the bending-points are the surface expression of *differences in rate of movement* of neighboring points in the horizontal projection of the geanticlinal axis.

RELATIVE AND ABSOLUTE HORIZONTAL MOVEMENT

If we neglect the displacement of the geanticlinal axis parallel to itself, as has been done, we find evidence only for the relative horizontal displacements of different points in the geanticlinal axis. The absolute horizontal movement may be considerable, but it cannot be inferred from the surface characters of the present geanticlines. If our interpretation of the evolution of the central basin of Timor is correct, important absolute horizontal movements must have taken place at greater depth, while the superficial parts moved at a slower rate. This conception agrees with the interpretation of the evolution of the Western Alps, as this has been

demonstrated by Argand.[1] Here likewise we see that in Mesozoic time geanticlines formed, separated by geosynclines, and that these have been moved in a horizontal direction. It may be that the southeastern Indian Archipelago will in the future arrive at the same stage as was long before reached in the Alps. As the horizontal movements proceed, the sea basins will narrow, and eventually the masses of the deeper parts of the present rows of islands will be pushed over the present Australian continent and the Sahul shelf which extends its borders. For a judgment, whether the active force tending to produce movement is directed to the southeast or to the northwest, as would follow from the conceptions of Hobbs[2] and Wegener,[3] no sufficient data are available.

[1] E. Argand, "Sur l'arc des Alpes occidencales," *Eclogae Geol. Helv.*, Vol. XIV (1916), p. 179.

[2] W. H. Hobbs, *op. cit.*, p. 91.

[3] A. Wegener, "Die Entstehung der Kontinente und Ozeane," *Die Wissenschaft*, 1920.

Reviews

The Oil and Gas Resources of Kentucky. By WILLARD ROUSE JILLSON, Kentucky State Geologist. Department of Geology and Forestry, Frankfort, Ky. 1919. Pp. 630.

This volume is a review and summary of the known oil and gas resources of Kentucky, found in strata ranging from the Ordovician to the Pennsylvanian. The "Calciferous" (Lower Ordovician) contains a small amount of oil and gas, but it is doubtful if it will ever be important commercially. The "Trenton" formation (Middle Ordovician) is an important source of oil, and the Cincinnatian has yielded some. The "Niagaran" (Silurian) is productive, but the Onondagan formation ("Corniferous," Middle Devonian) holds first place in the production of petroleum and natural gas in the state. The "Black Shale" (Upper Devonian) does not yield petroleum in commercial quantities, but some gas has been derived from it. The Waverly series (Lower Mississippian) contains oil and gas sands of importance. The St. Genevieve (=St. Louis limestone, Middle Mississippian) has not yielded petroleum on a commercial scale, but has yielded much gas. The Chester or Mauch Chunk formation (Upper Mississippian) is a good producer in eastern Kentucky. Both oil and gas occur in the Pottsville Conglomerate (Pennsylvanian). Neither petroleum nor gas is known to exist in formations younger than the Pennsylvanian, within the state.

R. A. J.

Descriptive Mineralogy. By W. S. BAYLEY. Appleton & Co., 1917. Pp. 542+xvii. $3.50.

To quote from the Preface, "The following pages are presented with the purpose of affording students a comprehensive view of modern mineralogy rather than a detailed knowledge of many minerals. . . . . The volume is not a reference book. It is offered solely as a textbook." Bearing these statements in mind, the work is one which may be highly commended, especially since it does not invade an overcrowded field.

As the title indicates, it is almost purely a descriptive mineralogy, lacking a discussion of crystallography, but containing material on the

composition, classification, formation, and alteration of minerals, as well as the principles and methods of blowpipe analysis. Appendices contain lists of minerals arranged according to their principal constituents and to their mode of crystallization, a list of reference books, and an abbreviated "key to the determination of minerals." The key is a device which classifies minerals according to luster, streak, color, and hardness and gives merely the pages in the main part of the text, where the detailed descriptions of the minerals may be found.

Perhaps the most noticeable defect is the paucity of photographs (less than forty), which probably accounts for the low price of the work. However, there are numerous drawings which remedy this deficiency to a large extent.

Minerals are classified according to their chemical composition. The arrangement of the silicates, a most difficult problem, is especially worthy of favorable comment. The book should be of great value as a text for advanced work in descriptive mineralogy.

D. J. F.

Detailed Report on Webster County. By D. B. REGER, West Virginia Geological Survey, Morgantown, W.Va. 1920. 671+xvi pages, 35 halftone plates, and 24 zinc etchings in the text, accompanied by a separate case of topographic and geologic maps. Price, including case of maps, charges prepaid, $3.00. Extra copies of topographic map, 75 cents, of the geologic map, $1.00.

Webster County contains the northward extension of the famous New River Coal group, as also the Kanawha group and the lower members of the Allegheny Series in its northern portion.

Recent Publications

—Henderson, C. W. Gold, Silver, Copper, Lead and Zinc in Colorado in 1918. Mines Report. [U.S. Geological Survey, Mineral Resources of the United States, 1918. Part I: 27. Washington, 1920.]

———. Gold, Silver, Copper, and Lead in South Dakota and Wyoming. [U.S. Geological Survey, Mineral Resources of the United States, 1917. Part I: 11. Washington, 1919.]

—Hess, F. L. Cobalt. [U.S. Geological Survey, Mineral Resources of the United States, 1916. Washington, 1919.]

———. Cobalt, Molybdenum, Nickel, Titanium, Tungsten, Radium, Uranium, and Vanadium in 1917. [U.S. Geological Survey, Mineral Resources of the United States, 1917. Part I: 29. Washington, 1920.]

—Hill, J. M. Arsenic, Bismuth, Selenium, and Tellurium in 1919. [U.S. Geological Survey, Mineral Resources of the United States, 1919. Part I: 3. Washington, 1920.]

———. Bauxite and Aluminum in 1919. [U.S. Geological Survey, Mineral Resources of the United States, 1919. Part I: 5. Washington, 1920.]

—Holdhaus, Karl. Sobre alguns Lamellibranchios Fosseis do Sul do Brasil. [Monographias do Servico Geologico E Mineralogico do Brasil. Vol. II. Rio de Janeiro: Imprensa Nacional, 1918.]

—Hopkins, O. B. Structure and Oil and Gas Resources of the Osage Reservation, Oklahoma. T. 25 N., Rs. 11 and 12 E. [U.S. Geological Survey, Bulletin 686-H. Washington, 1919.]

—Jones, E. L. A Deposit of Manganese Ore in Wyoming. [U.S. Geological Survey, Bulletin 715-C. Washington, 1920.]

———. Some Deposits of Manganese Ore in Colorado. [U.S. Geological Survey, Bulletin 715-D. Washington, 1920.]

—Kaiser, E. Bericht über geologische Studien während des Krieges in Südwestafrika. [Abhandlungen der Giessener Hochschulgesellschaft, II. Verlag von Alfred Töpelmann in Giessen, 1920.]

———. Der Eläolithsyenitlakkolith der Serra de Monchique im südlichen Portugal. [Separat-Abdruck aus dem Neuen Jahrbuch für Mineralogie, Geologie und Paläontologie, Beilage-Band XXXIX (Festband Bauer), Seite 225–267. Stuttgart, 1914. E. Schweizerbart'sche Verlagsbuchhandlung. Nägele and Dr. Sproesser.]

———. Studien während des Krieges in Südwestafrika. [Sonder-Abdruck aus der Zeitschrift der deutschen Geologischen Gesellschaft, Band 72, Jahrgang 1920, Monatsbericht Nr. 1–3.]

—KATZ, F. J. Abrasive Materials in 1918. [U.S. Geological Survey, Mineral Resources of the United States, 1918. Part II: 33. Washington, 1920.]

—KNOPF, ADOLF. A Geologic Reconnaissance of the Inyo Range and the Eastern Slope of the Sierra Nevada, California. With a section on the Stratigraphy of the Inyo Range, by Edwin Kirk. [U.S. Geological Survey, Professional Paper 110. 1918. Washington, 1919.]

———. Geology and Ore Deposits of the Yerington District, Nevada. [U.S. Geological Survey, Professional Paper 114, 1918. Washington, 1919.]

—LARSEN, E. S., AND LIVINGSTON, D. C. Geology of the Yellow Pine Cinnebar Mining District, Idaho. [U.S. Geological Survey, Bulletin 715-E. (Prepared in co-operation with the Idaho State Bureau of Mines and Geology.) Washington, 1920.]

—LEFFINGWELL, E. DE K. The Canning River Region, Northern Alaska. [U.S. Geological Survey, Professional Paper 109. Washington, 1919.]

—LEITH, C. K. International Control of Minerals. [U. S. Geological Survey, Mineral Resources of the United States, Part I: B. Washington, 1919.]

—LESHER, C. E. Coal in 1918. Part A. Production. [U.S. Geological Survey, Mineral Resources of the United States, 1918. Part II: 27. Washington, 1920.]

—LINDGREN, WALDEMAR, AND LOUGHLIN, G. F. Geology and Ore Deposits of the Tintic Mining District, Utah. With a Historical Review by V. C. Heikes. [U.S. Geological Survey, Professional Paper 107. Washington, 1919.]

—Liverpool Geological Society, Proceedings of the. Vol. XII, Part IV. Sessions the Fifty-Eighth, Fifty-Ninth, and Sixtieth, 1916–1919. [Liverpool: Royal Institution, Colquitt Street, 1920.]

—LLOYD, E. R. Petroleum in 1918. [U.S. Geological Survey, Mineral Resources of the United States, 1918. Part II: 32. Washington, 1920.]

—LLOYD, E. R., AND MATHER, K. F. Structure and Oil and Gas Resources of the Osage Reservation, Oklahoma. T. 20 N., R. 11 E. [U.S. Geological Survey, Bulletin 686-J. Washington, 1919.]

—LOBO, B. O Museu Nacional durante o Anno de 1919. [Museu Nacional do Rio de Janeiro. Rio de Janeiro, Imprensa Nacional, 1920.]

—LOUGHLIN, G. F. The Oxidized Zinc. Ores of Leadville, Colorado. [U.S. Geological Survey, Bulletin 681, 1918. Washington, 1919.]

—MCCASKEY, H. D. Quicksilver. [U.S. Geological Survey, Mineral Resources of the United States, 1916. Part I: 24. Washington, 1919.]

—MCLENNAN, J. C. Report on Some Sources of Helium in the British Empire. [Canada Department of Mines, No. 522. Mines Branch, Bulletin No. 31. Ottawa, 1920.]

—DE MARGERIE, EMM. Atlas établi sous la Direction de, Enquete sur les Richesses Minérales du Nord-Est de la France et des Régions voisines. [Paris, 1918.]

—MARSHALL, R. B. Results of Triangulation and Primary Traverse, 1911 and 1912. [U.S. Geological Survey, Bulletin 551. Washington, 1919.]

—MEINZER, O. E. Bibliography and Index of the Publications of the U. S. Geological Survey Relating to Ground Water. [U.S. Geological Survey, Water-Supply Paper 427. Washington, 1919.]

—Munition Resources Commission, Canada. Final Report of the Work of the Commission, November, 1915, to March, 1919, inclusive. [Toronto, 1920.]

—NORTHROP, J. D. Natural Gas Gasoline. [U.S. Geological Survey, Mineral Resources of the United States, 1917. Washington, 1919.]

—OSBON, C. C. Peat. [U.S. Geological Survey, Mineral Resources of the United States, 1917. Part II: 20. Washington, 1919.]

—PARDEE, J. T. Geology and Mineral Deposits of the Colville Indian Reservation, Washington. [U.S. Geological Survey, Bulletin 677. Washington, 1919.]

—Philippine Division of Mines of the Bureau of Science. The Mineral Resources of the Philippine Islands for the Years 1917 and 1918. [Manila, 1920.]

—RANSOME, F. L. Our Mineral Supplies: Quicksilver. [U.S. Geological Survey, Bulletin 666-FF. Washington, 1919.]

———. Quicksilver; with a Bibliography by I. P. Evans. [U.S. Geological Survey, Mineral Resources of the United States, 1917. Washington, 1919.]

—RANSOME, F. L., BURCHARD, E. F., AND GALE, H. S. Contributions to Economic Geology, 1917. Part I. Metals and Nonmetals except Fuels. [U.S. Geological Survey, Bulletin 660. Washington, 1919.]